ULTRAVIOLET IRRADIATION WITH ARTIFICIAL ILLUMINATION

A TECHNICAL, PHYSIOLOGICAL, AND HYGIENIC STUDY

BY

HANS E. RONGE

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AKADEMISK AVHANDLING
SOM MED NÅDIGT TILLSTÅND AV KUNGL. MAJ:T
FÖR MEDICINE DOKTORSGRADS VINNANDE OF-
FENTLIGEN FÖRSVARAS Å FÖRELÄSNINGSSALEN,
FYSIOLOGISKA INSTITUTIONEN, UNIVERSITETET,
UPPSALA, LÖRDAGEN DEN 17 APRIL 1948,
KL. 10 F. M.

AV

HANS E. RONGE
med. kand., Norrl.

UPPSALA 1948
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University of Uppsala, Sweden

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Contents.

Acknowledgements 5

I. Introduction 7

1. Basis and Purpose of the Investigation 7

2. A Brief Survey of Ultraviolet Radiology 10
Nature of ultraviolet radiation 11
Sources of visible and ultraviolet radiation 14
Measurement of ultraviolet radiation 20
Biological effects of ultraviolet radiation 22

3. Hygienic Applications of Ultraviolet Radiation 35
Ultraviolet radiation for interiors 36
Artificial sunlight treatments 38
Disinfection by ultraviolet radiation 40
Conclusions for the present investigation 42

II. The UV-Illumination System 44

4. Dosimetric Principles and Basic Design 44
Evaluation of effective radiation 46
Units and terms employed 48
Dosimetric relations of ultraviolet irradiation effects 50
The dosimetric design of the illumination 60

5. Technical Arrangement of the UV-Illumination System 61
UV-source 62
UV-reflector 69
UV-reflecting paints 72

6. Radiation Climate of the Experimental Rooms 74
Experimental rooms selected 74
Theoretical estimation 74
Experimental controls 77

7. Physical Methods Employed 79
Measurements of spectral energy distribution 80
Measurements of spectral transmission and reflection 90
Measurements of ultraviolet radiant intensities ... 91

8. A Comparison with Daylight Ultraviolet Conditions 92
Relation of UVE-intensity to the sun's elevation 94
Daily dosage of UVE at different seasons and latitudes 99
Annual dosage of UVE at different latitudes 100
The average daylight ultraviolet climate 102

III. The UV-Illumination Effects 104

9. A General Scheme of the Investigation 104
The statistical treatments 106
The reproduction of the results 108

10. Effects on Some Constituents of Blood 110
Analysis methods employed 111
Effect on haemoglobin concentration 115
Effects on calcium and phosphorus metabolism .. 117
The vitamin D experiment 121
Discussion 122

11. Effect on Physical Fitness 127
Test methods employed 129
Results 139
The vitamin D experiment 144
Discussion 145

12. Effect on Air-Borne Bacteria 148
Method of air-sampling 149
Infection-chamber experiments 150
Effect in the classrooms 152
Physical interpretation of the bactericidal effect.. 154
Discussion 162

13. Effect on Absenteeism 163
Discussion 170

IV. General Discussion 172

General conclusions 172
Practical conclusions 176

Summary 179

References 184

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H. E. R.

I.

Introduction.

CHAPTER 1.

The Basis and Purpose of the Investigation.

During the last few decades there has been rapid development in the field of artificial lighting. An outstanding progress is the possibility to control to a greater extent the spectral composition of radiant energy for illumination. This advance was reached by the introduction of gaseous-discharge lamps and fluorescent lamps in lighting practice. The spectral control has hitherto been applied mainly within the limits of the visible spectrum, with the development of "daylight illuminants". Early in this new era of illumination the suggestion was made, and experimentally realized, to utilize the technical possibility existing for the accomplishment of artificial daylight also with respect to the invisible components of natural daylight, primarily the ultraviolet radiation (Luckiesh, 1930, 1946; Porter, Egeler, and Sturrock, 1932; Oday and Porter, 1933). The idea has, however, not yet been investigated with respect to possible hygienic and physiological value and practical applicability. This has been the main purpose of the investigation presented here.

The primary reason for the study is found in the fact that important photobiological effects of daylight and sunlight, such as sunburn and synthesis of vitamin D, are limited to the ultraviolet part of the sun's spectrum and especially the very short-wave end of it. Outdoor natural daylight involves, for human beings, not only an illumination effect but also an irradiation effect, and indoor artificial illumination will never be an ideal substitute for daylight unless both of these general effects are secured. The natural daylight inside a common window is almost completely deprived of these particular rays, due to a selective absorption in the glass. There is in this respect a kind of biological shadow from ordinary windows, and even internal daylight is not a complete substitute for outdoor daylight.

In the interpretation of the ultraviolet irradiation effect of daylight an important geographical factor must be considered. In most inhabited parts of the earth the problem of the people might rather be to protect themselves against this kind of radiation; at least, there is no need of any supplementary irradiation. For the Scandinavian peoples, on the other hand, the natural supply of ultraviolet radiation might be expected to be less than for any other nation. The reason is that the short-wave ultraviolet part of the solar radiation is depleted to a much greater extent than the visible and the infra-red parts by the low sun elevations predominant there. The latitudes of Scandinavia, 55—70 deg. N., correspond to those of South Greenland, Alaska and Siberia, and the life of the Scandinavian nations is primarily dependent on the indirect supply of heat from ocean currents and atmospheric convection. In this way the climate of the air makes settling possible (cf. MARKHAM, 1947), but the solar radiation climate may be expected to be less favourable, especially with respect to the supply of ultraviolet radiation during the long winter. The problems concerning the possible hygienic importance of a supplementary administration in some form of ultraviolet radiation may then be considered as a special, or specific, interest of Scandinavia.

There is, on the other hand, undoubtedly manifest a tendency to exaggerate the vital importance of both natural and artificial sunlight and, especially, to make extravagant claims for it as a therapeutic force (cf. LAURENS, 1935). Among the variety of effects hitherto recognized of ultraviolet energy on the human body only the photo-synthesis of vitamin D in the skin is proved as an essential. It is a generally accepted fact that the ultraviolet component of daylight constitutes the main natural source of this vitamin for both man and animals. The pronounced geographical and seasonal variation of the incidence of rickets in infants may receive a complete explanation on this basis. The main action of vitamin D in the human body is to promote the calcification of the bones, and the vitamin may then be assumed to be of special importance for the growing body. The potential risk of a vitamin D deficiency in infants during the long winter in Sweden is now well recognized and, in the main, is successfully counteracted by the administration of vitamin D preparations to all babies and infants. In older infants, as school children, the clinical manifestations of a possible vitamin D defi-

ciency are not very marked, and even rather unknown, and prophylactic measures have not the same prevalence. Hence, school children provide a suitable experimental material for an investigation on both the physiological consequences of the lack of natural ultraviolet radiation and the possible effects of a supplementary administration of it during the winter. The mechanisms underlying the radiation effects are secondary questions in this respect, and are not the subjects of the present investigation. The possibility may not *a priori* be excluded that a continuous ultraviolet irradiation of children also exerts other effects of health-improving character than does a simple administration of pure vitamin D. The present state of our knowledge — or rather our lack of exact knowledge — in this field does not justify a presumptuous dismissal of ultraviolet radiation as an additional factor of hygienic and biological importance.

In contrast to the visible and infrared components of sunlight, no immediate sensation exists for man when the ultraviolet component is lacking; for light and radiant heat the body is provided with special sense organs, but ultraviolet radiation acts in complete silence. This adds further importance to ultraviolet as a potential factor in the radiation climate, especially from the hygienic point of view. The most rational way of securing people their possible requirement of ultraviolet in the dark season should then be to combine it inherently with its perceptible relevants, i. e., to utilize the obvious claim for artificial illumination during the winter as a means for the regulation of the silent need of ultraviolet radiation. Indoor artificial lighting should provide a *radiation climate* with as much as possible of the biological effects of outdoor natural daylight. The special feature of such a manner of administration should be the continuous low-intensity irradiation, in the place of the massive high-intensity exposures used in physical medicine and in the common form of artificial sunlight treatments.

Besides the direct effects on the occupants it may be expected that an artificial lighting system with the simultaneous emission of ultraviolet radiation also exerts a favourable bactericidal action in the room. The effect in this respect of common artificial illumination is practically none owing to the low intensity and the lack of powerful ultraviolet radiation. Natural daylight from windows maintains some part of the germicidal power, due to the comparatively high intensity of blue and near-ultraviolet radiation (cf. Hol-

LAENDER, 1946). The most effective radiation for killing bacteria is, however, the ultraviolet wavelengths corresponding to the short-wave limit of the solar spectrum, and the maximum effectiveness is found at still shorter wavelengths. This germicidal power of short-wave ultraviolet radiation has in recent years been effectively utilized as a basis for sanitary control of air-borne infections, furthered especially by the development of the low-pressure mercury lamp (cf. MOULTON, 1942). An ultraviolet illumination as outlined here would combine the germicidal effect in the room with the irradiation effect on the occupants.

The International Commission on Illumination (I. C. I.) has constituted at the 1931 Cambridge congress a Committee on Ultraviolet Radiation, with the programme to evaluate physical measurements of ultraviolet radiation as emitted by modern light sources. The Reports of the Secretariat-Committee to the latest congresses, 1935 and 1939 (I. C. I., 1937, 1942), deal particulary with problems concerning the application and standardization of spectral measurement devices, but there are also collected data and discussion on the biological effects of ultraviolet radiation, which are of importance to the physical aspects of an 'ultraviolet illumination.' In the last report (I. C. I., 1942) it is emphasized that "It is for the medical science to express views as to the desirability of the general use of sources of ultraviolet radiation"; the present investigation may be considered as a first attempt to give an experimentally founded answer to this basic problem of the field.

CHAPTER 2.

A Brief Survey of Ultraviolet Radiology.

The field of ultraviolet radiology involves aspects from a number of different sciences, as physics, chemistry, technology, climatology, biology, hygiene, and medicine, and most of them are in some form represented also in the present study. It is, however, far beyond the scope of this chapter to review the entire field. Only some glimpses of basic knowledge and data of special interest to the present purpose of ultraviolet illumination will be given. There are many ex-

tensive and excellent treatises published in recent years on both the entire field and special regions of it. Exhaustive reviews are given by Ellis, Wells, and Heyroth (1941), Meyer and Seitz (1942), and Déribéré (1947), and the volumes of Duggar (1936) include valuable articles on both physical and biological problems in the field. An essay on chemical aspects of light is given by Bowen (1942). Luckiesh (1930, 1946) has treated the field particulary from the aspects of interest here, and Harris (1932) has given a synopsis of the ultraviolet technology. The reviews of Büttner (1938) and de Rudder (1938) include a number of climatological aspects, and predominantly biological reviews are given by Laurens (1933, see also Laurens, 1938, 1941, 1944), and Blum (1941, see also Blum, 1943, 1944, 1945), and therapeutic reviews by Ellinger (1941) and Krusen (1941). Authoritative articles on the therapeutic applications of ultraviolet radiation are found in *Handbook of Physical Medicine*, published by the Council on Physical Medicine, U. S. A. (1945). Some excellent articles on different aspects of ultraviolet radiation are also found in the extensive volume *Medical Physics*, edited by Glasser (1944; see the articles by Blum; Forsythe and Adams; Laurens; and Krusen and Elkins). Some basic articles on the hygienic applications of ultraviolet as a bactericidal agent are collected in the volume *Aerobiology*, published by Moulton (1942), and a recent review is given by Hollaender (1946).

The Nature of Ultraviolet Radiation.

The special character of ultraviolet radiation as a powerful environmental factor is due to its high quantum energy. In the interaction of radiation and matter, with regard to both emission and absorption of radiation, the wave theory of radiation must be replaced, or completed, by the quantum theory in order to permit a physical interpretation of the processes. Radiation is emitted and acts as discrete packets of energy, or quanta, and the magnitude of the quantum (q) is related to the frequency of the radiation (ν) according to the law of Planck:

$$q = h\,\nu$$

where h is Planck's constant, which has a value of $6.6236 \cdot 10^{-27}$ erg-seconds.

The frequency (ν) and the wavelength (λ) of the radiation are related to the velocity (c) of light ($3 \cdot 10^{10}$ cm/sec.) by

$$c = \nu \cdot \lambda$$

A basic assumption in the quantum theory of radiation and hence in the whole of photochemistry and photobiology, is that of *fixed energy levels* in the atoms and molecules. An atom in its normal state contains a given amount of energy, representing the lowest level of these fixed levels; they are in some way connected with the electronic structure of the particle (atom or molecule). To change from a low energy level to a higher level the particle must absorb a quantum of energy equal to the difference in energy between the two levels. The higher levels are unstable, representing different degrees of excitation, and the highest level is the *state of ionization*, when an electron is separated from the particle. In order that ionization may occur the quantum absorbed by the atom or molecule must have a certain minimum energy.

The source of excitement may be thermal energy, electric energy or radiant energy, but it always provides the absorption of quanta which will supply the exact energy required to raise it from a low level to a high level. One way for the particle to return from the excited state to the normal state is *by emitting as radiation the same quantum of energy as was absorbed.* This is the basic process of all light-sources; when the excitement is produced by heating the emission of radiation is called *incandescence* and when produced by electric or radiant energy it is termed *luminescence* (electro-luminescence and photo-luminescence, respectively; the latter is termed fluorescence when the emission follows immediately after the excitement and phosphorescence when the emission is delayed). The tungsten-filament lamp is an incandescent radiator, while electro-luminescence is the principle of the vapour-discharge lamps such as the mercury arc, and fluorescence is utilized in the recently developed fluorescent or luminous tubes. The emission spectrum of a vapour-discharge lamp shows a number of distinct lines at different wavelengths, i. e., quantum sizes, each corresponding to the *difference* between two out of the fixed energy levels of the atom of the gas. The excitement is produced by the impact of an electron of the current passing through the vapour.

The molecules possess a great number of quantized stages, due to mutual effects between the atoms, and hence a great number of wavelengths, usually as wavelength bands or a continuous spectrum, which are emitted or absorbed. The emission is mainly produced by heating, as in incandescent lamps, or by photo-luminescence, as in fluorescent lamps.

The *absorption of radiation by molecules* is of special interest to photochemistry and photobiology. The capture of a quantum may give rise to an excited molecule, or if the absorbed quantum is sufficiently large it may produce ionization of the molecule. The excited or ionized particle is likely to start or take part in chemical reactions. Ionization obviously will be more often produced by short wavelengths (large quanta) than by long ones. Absorbed quanta of smaller size may produce fluorescence, or excited molecules, or the energy may be degraded by collisional or other processes into heat-energy (see Bowen, 1942).

Instead of dealing with single quanta and single molecules, which make the numerical values very small, it is convenient to use the *gram molecule* ($6.023 \cdot$

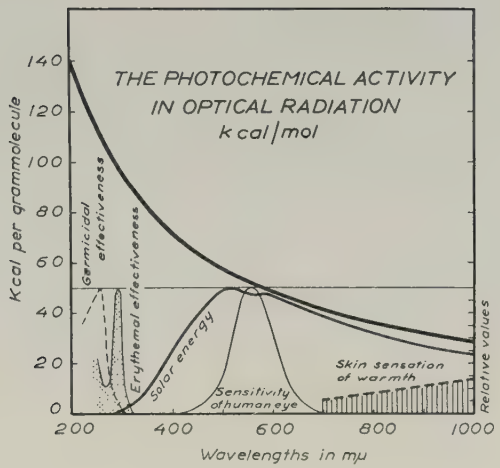

Fig. 1. The ratio of quantum energy to wavelength in the near-ultraviolet, visible, and near-infrared spectrum seen in relation to the corresponding three fundamental radiation effects on man, viz., chemical action, luminous action, and heating action.

10^{23} molecules) as the reference amount of matter. The quantum energy in a given wavelength may then be expressed in kilogram calories per gram molecule (the Einstein-unit), giving a measure of the amount of energy which would be absorbed if every molecule of a gram molecule (mole) absorbed a quantum of the frequency or wavelength in question. Thus, the magnitude of a quantum of energy of wavelength 300 mμ, of frequency 10^{15} sec.$^{-1}$, is $6.62 \cdot 10^{-12}$ ergs, and a gram molecule number of the above quanta is equal to 95.27 kilogram calories. The energy differences in electronic transitions is about 20 to 200 k. cal. per gram molecule. To produce the same electronic excitement by heat alone would require exceedingly high temperatures.

Fig. 1 shows the relation of quantum energy to wavelength within the spectral range of interest here. Above about 760 mμ the magnitude of the quanta are too small to excite even the sensitive visual substances of the retina, and the energy is degraded into heat. Due to the increasingly superficial absorption of longer infra-red wavelengths in the skin the sensation of warmth for equal amounts of radiation increases toward the long-wave infra-red. The *visual substances* of the eye are adapted to magnitudes of quanta corresponding to the wavelength region 400—760 mμ, the visible spectrum. At the limit of about 315 mμ the quanta become sufficient to produce *decomposition of cellular proteins*, and the same upper quantum or wavelength limit has the *photo-synthesis of vitamin D*. The short-wave end of the solar spectrum is situated at 295—320 mμ according to the elevation of the sun above the horizon. At wavelengths below about 280 mμ the *lethal effects* of radiation are dominant.

The long-wave ultraviolet region 315—400 mμ is sometimes called UVA, the medium-wave region 280—315 mμ UVB and the short-wave region below 280 mμ UVC.

The Photochemical Principles.

The first act in any photochemical reaction is the absorption of a quantum of energy by an atom or molecule in the reacting system (the Equivalence Law of Einstein). If every absorbed quantum results in the transformation of the absorbing molecule, the *quantum yield* of the reaction is said to be unity. This is, however, not always the case, and the yield usually varies for different magnitudes of quanta, i. e., for different wavelengths. The spectral variation of the relative efficiency factor is expressed by the *action spectrum* of the reaction. The number of molecules transformed is determined by the number of absorbed quanta times the corresponding efficiency factor of every wavelength. This is the photochemical principle underlying the use of *biologically-weighted units of radiant energy*, frequently applied in later chapters.

The yield of every wavelength is commonly but incorrectly related to the amount of energy absorbed. This amounts (Q) is expressed by the equation

$$Q = N \cdot h \cdot \nu$$

where N equals the number of quanta of the magnitude $h\nu$. According to the equivalence law the correct measure is obviously not Q but N in the equation above; the action spectra obtained by energy measurements must be corrected for relative number of quanta (Blum, 1944). Considering the uncertainty of most of the biological action spectra this correction does not, however, add significantly to their reliability.

The equivalence law involves the two other laws inherently associated with photochemistry: the Grotthus-Draper law, stating that only those wavelengths of radiation which are absorbed by a system may produce photochemical reactions in that system, and the *reciprocity law* of Bunsen and Roscoe, stating that the product of the duration (t) and the intensity (E) of radiant flux which will produce a given quantity of a given chemical reaction is a constant:

$$E \cdot t = k$$

Numerous photobiological processes follow this law quite accurately within certain limits of exposure times, e. g., the threshold of erythema in sunburn and the killing of bacteria. The term *dosage* is convenient to use for the product of intensity and time (Et), or, in other words, the quantity of energy applied.

Sources of Visible and Ultraviolet Radiation.

The sources of optical radiation, including the ultraviolet, visible and infra-red wavelength regions, may conveniently be divided into two main groups: thermal radiators and luminescent radiators.

The essential component in *thermal radiators* is a heated solid body, as in radiant heaters or tungsten filament lamps. Such radiation consists of quanta of a great number of sizes, and appears as a wide

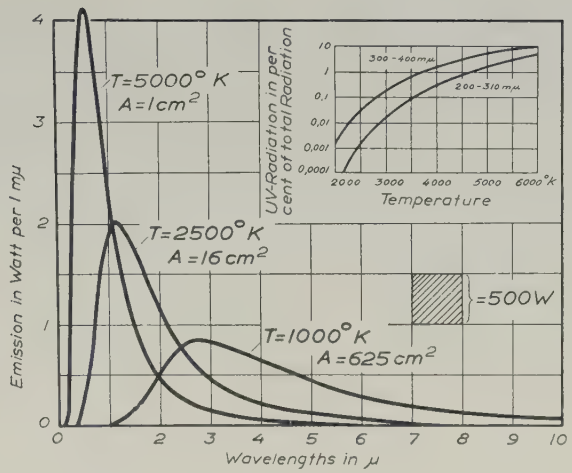

Fig. 2. Spectral energy distribution in the radiation from an ideal black body of different surface temperatures (T). The radiating surface (A) is chosen so that the total emission is similar for all cases. The inset diagram shows the percentage of ultraviolet energy for different spectral regions in the total emission at different temperatures. (After Meyer and Seitz, 1942, and Luckiesh, 1930.)

continuous spectrum. The region of maximum intensity of the spectrum shifts toward shorter wavelengths as the temperature of the body increases, and the body emits considerably more radiant energy as a whole. The physical law describing the spectral energy distribution as a function of temperature was formulated, for an ideal 'black body', by Planck in 1900; in the derivation of this formula the constant h was first found to be essential. Fig. 2 shows some curves calculated by this equation for different temperatures. The spectral energy distribution of the *tungsten-filament lamp radiation* is approximately similar to that of a black body of about 2,800° K, and the maximum temperature of the filament, determined by its melting point, is about 3,200° K. It is obvious that *artificial thermal radiators are inefficient sources of ultraviolet radiation;* the temperature of the system is not sufficient to supply energy to the molecules for the emitting of larger quanta. Only about 1/10,000th of the energy emitted by the tungsten filament is found in the wavelength region capable of producing such biological effects as sunburn and synthesis of vitamin D, and most of this radiation is absorbed by the glass bulbs of such lamps (see Forsythe and Christison, 1930). However, tungsten filament lamps with the bulb

of quartz or a special ultraviolet-transmitting glass have been claimed for as therapeutic sources of ultraviolet radiation ("Vitalux", "Mazda CX lamps", see, e. g., DAMMEYER and SKAUPY, 1930).

The most important source of radiation for living organisms is *the sun*. The radiation characteristics of the solar spectrum correspond approximately to that of a black body of the surface temperature 5,500° K (see FORSYTHE and CHRISTISON, 1930). The relative content of ultraviolet radiation is several hundred times that of the incandescent light, but the short-wave spectral limit is found abrubtly at 290—295 mμ at the surface of the earth. This limit of the spectrum is due to the absorption of shorter wavelengths during the passage of the rays through the atmosphere. The absorption of the chemically most active radiation, wavelengths below 200 mμ, produces ionization of the highest layer of the atmosphere, and a formation of ozone from oxygen is induced. *The solar-formed ozone provides a very effective filter for wavelengths below 300 mμ* and is the main factor determining the short-wave limit of the sun's spectrum at the surface of the earth. Thus, the solar radiation itself forms the filter in the atmosphere, which screens out the wavelengths of a chemical activity too high for permitting organic life. The maximum energy in the solar spectrum is present in the region 500—600 mμ, where the sensitivity of the human eye has its maximum; an example of the rational adaptation of humans to sunlight as the paramount environmental factor.

A powerful natural source of ultraviolet radiation is furthermore the *radiation from the sky*. The scattering of light in the atmosphere is, according to the law of RAYLEIGH, inversely proportional to the fourth power of the wavelength, and hence affects the blue and ultraviolet wavelengths in the solar radiation more than the red and infra-red wavelengths. As will be discussed in a later chapter the intensity of ultraviolet radiation of wavelengths below 315 mμ on a horizontal surface fully exposed to sun and sky is more than half due to the sky radiation.

Efficient artificial sources of ultraviolet radiation are found only among the *luminescent radiators*. When light is radiated by some process in which high temperature is not the main consideration, the light is said to be due to luminescence (popularly referred to as "cold light"). The spectrum of luminescent radiation differs from that of thermal radiation in that it is always discontinuous, some-

times consisting of a group of bands, sometimes of narrow lines and, occasionally, of a combination of the two. The wavelengths of the bands or lines are characteristic of the material used. Band spectra are produced by radiating molecules, while line spectra are due to single atoms. Luminescence may be excited in various ways but ultimately these are the same in that they all involve a disturbance of the natural energy of the electrons. Of greatest interest is the *electro-luminescence* excited by the impacts in atoms of free electrons set in motion by an electric field, and the *photo-luminescence*, excited by the absorption of quanta emitted from other atoms. To the first class belongs the radiation emitted by vapours and gases in electric arcs and sparks, and the second group includes radiation by fluorescence and phosphorescence.

The *mercury vapour arc* in quartz is a particularly strong source of ultraviolet rays and is widely used for experimental studies as well as being the most common source of ultraviolet for therapeutic purposes. Quartz is used for the enclosure as it is transparent for radiation of wavelengths down to 190 mμ, while ordinary glass will transmit only rays of wavelengths longer than 320 mμ. These sources are often referred to as quartz mercury arcs, or by the misnomer "quartz lamp." Several types of such lamps are on the market. The wavelengths of emitted lines are virtually the same for all, although the relative intensities may vary to some extent. A main factor determining the relative spectral output is the *vapour-pressure of the mercury*, and hence the temperature of the arc. The common therapeutic "hot" mercury arc operates at a vapour-pressure of about one atmosphere and emits distinct lines distributed over the ultraviolet and visible region (see, e. g., Rössler, 1940; Oranje, 1943; Forsythe and Adams, 1944; Coblentz, 1945, 1946). Provided with an outer bulb of special glass, absorbing radiation of wavelengths shorter than about 280 mμ, such lamps are sometimes called "*sun-lamps*". Such a type is employed in the present study for the purpose of ultraviolet illumination, and will be described in later chapters.

Special types of sun-lamps were developed in the U. S. A. (General Electric) more than a decade ago, the S-1 and S-2, consisting of a tungsten filament in parallel with a small mercury arc and thus combining the thermal emission of the tungsten filament with mercury-vapour lines (Forsythe, Barnes, and Easley, 1931). The

spectral limit in the ultraviolet region is about 280 mμ, which is determined by the special glass of the bulb (see A. H. Taylor, 1931). Considerable amounts of light and infra-red are emitted, and the sources were previously intended also for general use as "dual purpose lighting", i. e., producing general illumination and ultraviolet irradiation at the same time (Luckiesh, 1930; Porter, Egeler, and Sturrock, 1932). The bulbs of the lamps last for about 200 or 300 hours of burning time and must then be replaced.

Other types of sun-lamps which in different modes combine the emission of mercury lines with thermal radiation from a tungsten filament, enclosed in the same bulb, are "the type G mercury glow lamp" and the "Ultra-Vitalux lamp." They are designed for therapeutic purposes (see Meyer and Seitz, 1942; Forsythe and Adams, 1944).

The considerable amounts of visible radiation emitted from the mercury vapour lamps make them *powerful light-sources*, and they are in recent times widely used in combination with tungsten filament lamps for industrial lighting. The strong violet and green lines of the mercury spectrum balance the predominance of yellow and red radiation in the incandescent light with the result of a *white*, "*daylight illumination.*" The discontinuity of the spectrum may cause some disturbances in the exact evaluation of colours, but with suitable proportion of mercury and incandescent light these are usually of no practical importance (see Matthews, 1940). In this modern use of mercury arc lamps for illumination no attempt is made to utilize the ultraviolet radiation for a simultaneous irradiation purpose; the quartz tube of the mercury arc is enclosed by a bulb of ordinary glass, absorbing most of the radiation of wavelengths below 315 mμ (see p. 37).

New developments of mercury arcs are those operating at very low as well as very high mercury-vapour pressures. The *low-pressure mercury arc* ("cold quartz arc") emits most of its energy as resonance radiation of the wavelengths 253.7 and 185.0 mμ. Confined in bulbs or tubes of special glass highly transparent for wavelengths longer than 230 mμ these arcs are *efficient sources of radiation for killing bacteria and molds* and are known under trade names as Germicidal Lamps, Sterilamps, etc. Wavelengths shorter than 230 mμ must be absorbed by the enclosing glass in order to prevent excessive

ozone formation (Coblentz, 1942). Technical data of these lamps are given by Buttolph (1942) and Rentschler (1942).

An important application of the low-pressure mercury arc was made by the development of the *fluorescent lamps*, increasingly used for indoor illumination. In these sources electro-luminescence is combined with photo-luminescence in the way that the short-wave ultraviolet radiation generated in the low-pressure mercury arc is used for producing fluorescence in a thin layer of fluorescent materials (phosphors) coated on the inside surface of the glass envelope of the arc. By suitably choosing and mixing the phosphors a great control over the spectral character of the emitted radiation is possible. These lamps consitute the *modern sources for providing artificial daylight* (see, e. g., Kruithof, 1941). By means of special phosphors it is possible to use fluorescent lamps as sources of ultraviolet energy also, with the radiation extending through the long-wave ultraviolet region into the medium region ("fluorescent sun-lamps", etc., Luckiesh, 1946; Clapp and Ginther, 1947).

The *high-pressure mercury arcs*, operating at vapour pressures of 10—100 atmospheres, are powerful sources of long-wave ultraviolet and visible energy. The spectrum consists of a continuum from about 280 mμ and toward longer ultraviolet and visible wavelengths, with the mercury lines superimposed (see fig. 21, p. 89). Shorter wavelengths than about 280 mμ are almost lacking in the spectrum owing to the inversion of the resonance lines occuring at high vapour pressures. The luminous efficiency is very high, being 65 lumens per watt, as compared to about 12 lumens per watt for a tungsten filament lamp and about 35 lumens per watt for a medium-pressure mercury arc. They are used for optical but also therapeutic purposes (see Meyer and Seitz, 1942), and have recently been also employed for sun-lamps (see Coblentz, 1946; Beggs, 1947).

Common to all mercury vapour arcs is that they will not start on the low voltage necessary to operate them, and several special methods are used for this purpose. Also, these arcs have a negative voltage-current relation. Thus as the current increases, the voltage necessary to maintain this current decreases, i. e., the current would increase to a value that would destroy the lamp if there were no means to limit it. Both the methods of starting the lamp and limiting the current through it are incorporated in the transformer or choke coil used in its operation.

The Measurement of Ultraviolet Radiation.

The measurement of radiation consitutes a basic assumption for the quantitative study of photobiological processes, but is, however, by no means a simple problem. The value of much of the published material is greatly reduced by the absence of accurate measurements and adequate identification of the spectral distribution of the radiation employed. The effects of ultraviolet radiation are highly selective so that *the measurement of ultraviolet radiation requires measurements of narrow spectral regions*; the active regions are different for different photobiological effects. The evaluation of a given radiation in regard to a given effect may be carried out in two different ways. The one is to use a measuring device with a spectral response similar to that of the effect. The other is to measure the radiation for each wavelength after having resolved its spectral components, and then to make the evaluation arithmetically with respect to the spectral efficiency curve of the biological effect. In the present study it is mainly this second procedure which has been employed. The methods will be described in a later chapter and only a brief outline of basic devices is given here. Recent reviews of radiation measurements with special respect to photobiological effects are given by, e. g., Taylor and Holladay (1931), Brackett (1935, 1936), Seitz and Meyer (1942, 1943), and Henschke and Schulze (1942). Mörikofer (1939) has reviewed the methods of meteorological radiation measurements. Recent developments in the U. S. A. are described by Luckiesh (1946).

Receivers of radiation, used for indication or integration of quantity of radiation, are thermopiles, photoelectric devices, photo-chemical reaction systems, and the photographic plate. The *thermopiles* are uniformly sensitive throughout the spectrum and are useful as standard instruments but not very adapted to field work. The *photoelectric cells* are selective detectors of radiant energy and appropriate types may be chosen for different spectral regions. Two types are to be differentiated: the high-vacuum or gas-filled emissive type (phototubes) and the barrier-layer or self-generative type. Among the *photoemissive cells* particularly the cadmium cell, introduced by Dorno (1919), is suitable for ultraviolet measurements. By means of proper filters it is possible to provide a sensitivity curve in close agreement with the relative erythema response of human skin (see Büttner, 1931). The Rentschler Ultraviolet Meter comprises special uranium, thorium, cerium, titanium and tantalum photoelectric cells connected to a glow relay tube and is used both as indicating intensity-meter and time-integrating energy-meter (Rentschler, 1930). Other similar instruments are developed by A. H. Taylor (1934 a), who has described useful instruments for

measuring germicidal energy emitted from the low-pressure mercury arc (A. H. Taylor, 1944, 1945). The applicability of the *barrier-layer photocell* with selenium as the sensitive material for measurements of biologically-active ultraviolet radiation is described by Krefft and Rössler (1936). The maximum sensitivity of these cells is found about 550 mμ but extends down to the medium-wave and short-wave ultraviolet regions; the layer of lacquer on the surface ought to be replaced by a quartz plate for measurements in ultraviolet.

The *photochemical methods* of measuring ultraviolet energy are now in the main supplanted by the photoelectric methods. Among the chemical methods previously used, ought to be mentioned the zinc sulphide method of Clark, the acetone-methyleneblue method of Webster, Hill, and Eidinow, and the oxalic acid method of Anderson and Robinson; all these methods are described and standardized by Mayerson (1935 a). The UV-Dosimeter of I. G. Farben has been widely employed in Europe, especially in climatological works (see Büttner, 1938; Landsberg, 1937; Meyer and Seitz, 1942), but is no longer available. A number of methods based on the fluorescence excited by ultraviolet radiation in special glasses etc. have also been described (see Taylor and Holladay, 1931; Seitz and Meyer, 1942). Inherent difficulties of all these methods of measuring radiant energy are the uncertainty of the spectral response curve and the variations caused by temperature and other external influences. In the main they cannot be recommended for other purposes than rough estimations.

The *photographic plate* is used for intensity measurements primarly in connection with spectral apparatus. The sensitivity of normal plates reaches down to wavelengths of about 250 mμ, and for shorter wavelengths sensitized plates are available. Photographic methods are applied for spectroradiometry in the present investigation, according to the procedures described by Sawyer (1945), Lewis (1946), and others, see Chap. 7.

For the isolation of narrow or broad, definite spectral ranges of ultraviolet radiation there are a number of *filters* available, solid or in solution (see Meyer and Seitz, 1942). By combining selectively transmitting filters with selectively reacting photocells a great number of resultant spectral sensitivity-curves of the devices are obtainable. A useful solution filter for the isolation of the biologically important spectral range below 320 mμ was developed by Bäckström (1933, 1940), with cobalt- and nickel-sulphate as essentials. It has also been employed in the present investigation, see Chap. 7.

When the results are to be expressed in *absolute units of energy* the measuring device must be calibrated against a standard source of energy. The non-selective thermopiles are best suited for such measurements, and the use of selective instruments as employed here provides special considerations (see p. 81). A *standard-source of ultraviolet radiation* was described by Krefft, Rössler, and Rüttenauer (1937) and has been available for the present investigation. A discussion on standard-lamps for absolute measurements is given in the report of the International Commission on Illumination, 1939 (I.C.I., 1942).

Biological Effects of Ultraviolet Radiation.

Every biological effect of ultraviolet radiation on the human body is caused by its action on the outer membranes, mainly the skin. The effects are, however, not limited to those organs, as substances photochemically formed by the direct action on the skin are absorbed through the skin and distributed throughout the body by lymph and blood. The photobiological effects may then be suitably grouped as direct and indirect, the former including the *local changes* at the place of the absorption, and the second including the general, *systemic effects* induced in the body by the irradiation. In the scope of these pages it is impossible to give more than a brief outline of the theme, and the references must, in order to limit the bibliography, mainly be given to recent reviews and monographs.

For the design of a continuous ultraviolet irradiation, as was to be employed in the present investigation, the state of knowledge with regard to the dosage and spectral relations of irradiation and effect is of basic importance, and will be discussed in detail in a following chapter.

The Photoerythema of the Skin.

The almost immediate reddening of the skin during and after irradiation by sun or a sufficiently strong artificial source is due to the heating by the long luminous and infra-red wavelengths. The skin erythema known as sunburn (photo-erythema) differs from the similar change caused by heat in that it develops only after a *latent period* amounting to 2 hours on the average but ranging from 1 to 7 hours. Furthermore it is not as fleeting as heat erythema; the redness gradually increases and attains a maximum usually after 7 hours, and may subside after 18 to 24 hours. According to the intensity of the irradiation it may be combined with blistering and haemorrhage.

That heat is not the cause of sunburn was proved by E. P. Widmark in 1889. The modern era of photobiological research began with the pioneer work of Niels R. Finsen, who in 1893 showed that sunburn is caused by the ultraviolet, "chemical" rays present in sunlight, and later introduced ultraviolet irradiation as treatment of the skin tuberculosis known as *lupus vulgaris* (see Lomholt, 1946). The present state of knowledge with regard to photoerythema is

founded in numerous works and the historical development cannot be considered here.

Using ordinary intensities, the longest wavelengths that produces erythema are between 315 and 320 mμ. The curve representing *relative effectiveness of different wavelengths* rises to a maximum at 297 mμ, descends to a minimum at 280 mμ, then rises to another maximum between 250 and 240 mμ and extends to an undertermined shorter wavelength (K. W. Hausser 1934; see also p. 51).

The depth of penetration of different ultraviolet wavelengths into the skin is an important factor for the interpretation of the effects. Only a very small portion of wavelengths below 300 mμ is transmitted through an ordinary thick epidermis (80—100 μ) while longer wavelengths may reach the capillary layer in considerable amounts. The horny layer of the skin shows an increasing absorption for wavelengths below 300 mμ, with a first maximum at 280 mμ (Bachem, 1931). By regarding the corneum as a protecting screen for the Malphigian layer cells beneath it, the characteristic action spectrum of erythema may be explained as derived from the absorption spectrum of a typical protein constituent of living cells (Mitchell, 1938). By the decomposition following this absorption it is assumed that *vaso-dilating H-substances* acting on the cutaneous capillaries are liberated, and the presence of such substances in the skin and the blood after irradiation is also proved in many different ways (see Laurens, 1941). The latent period of the erythema is explained as due to a slowly diffusing "H-colloid." Ellinger (see Ellinger, 1941) has given evidence for a direct photochemical formation of histamine from histidine occurring especially for radiation about 250 mμ and being responsible for the paler and more rapidly subsiding erythema produced by these shorter wavelengths. A comprehensive, tentative scheme of the processes underlying the photoerythema is recently given by Blum (1945) and some new additions to the theories are made by Blum and Ferus (1946 a–b).

The importance of ultraviolet wavelengths longer than 320 mμ for the irradiation effects on the skin was first demonstrated by Lomholt (1936) at the Finsen Institute, who showed that the therapeutic effect of irradiation on lupus is mainly due to the spectral region 320—350 mμ and that these rays are also capable of producing erythema and, especially, pigmentation, when applied in sufficient doses. The work of I. Hausser (1938), extended by others (see Lau-

RENS, 1941; BLUM, 1943), has given further evidence of *specific effects of long-wave ultraviolet radiation for the pigmentation* occurring after ultraviolet irradiation. The effect of the longer ultraviolet rays is assumed to be a transformation of an uncoloured leukomelanin, present in the basal cells of epidermis, into dark melanin; the formation of leukomelanin seems to be induced by the erythema-effective wavelengths below about 320 mμ. The photochemical mechanism of the photo-pigmentation is thus to be distinguished from that of the erythema. The action spectrum of photo-pigmentation has a flat maximum in the region 340—380 mμ but extends to about 420 mμ. The transformation of leukomelanin into melanin has no latent period but requires the presence of oxygen; it is assumed to be an oxidation, and is affected by the presence of sexual hormones. The energy of radiation required for producing an immediate pigmentation without preceeding erythema by long-wave ultraviolet is of the order of 500 times that for producing erythema by the wavelength 297 mμ (cf. p. 51). A recently published action spectrum combines the erythema and tanning effectiveness of ultraviolet radiation (LUCKIESH and TAYLOR, 1939).

The *susceptibility to sunburn* may vary considerably between different individuals. There is a seasonal variation with a spring maximum, a summer minimum and a fresh rise in the autumn (see ELLINGER, 1941). Blondes are from 40 to 170 per cent more sensitive than brunettes. Endocrine influences seem to play an important part and are probably bound up with the sex function; before and during puberty the sensitivity is less than one half of that of sexual maturity age, and there is a decrease of sensitivity also in the involutionary age. Women are about 20 per cent less photo-sensitive on the year's average than men.

The most important role for the *adaptation of the skin* to erythema-effective radiation is the thickening of the epidermis, mainly its horny layer (corneum). This may be regarded as an effect of increased metabolism and growth of the skin, induced by the improved blood supply and also by the probable liberation of growth-promoting substances (see BLUM, 1943). The peeling which may follow the irradiation may be seen as a sign of this increased growth rate of the skin. The pigment appears almost exclusively in the basal cells of epidermis and is the sun-shade for the dermis as the horny layer is the sun-shade for the epidermis (MIESCHER, 1931; cf. LAURENS, 1935).

A number of other effects, chemical and physico-chemical, occurring in the skin after ultraviolet irradiation are described, as increased bactericidal properties of the lipids of the skin, increase of sulfhydril-concentration, rise of the cholesterol content, destruction of enzymes, change of fluorescence, etc., etc., (see ELLINGER, 1941; LAURENS, 1941; BLUM, 1943). Irradiation is said to cause an intensification of the skin eruptions of epidemic diseases (smallpox, morbilli) when applied during the incubatory period (WORINGER, 1931).

Malignant tumors have been produced in experimental animals as a result of excessive exposures to ultraviolet radiation given either as sunlight or from artificial sources. The exposures needed are usually far outside the range in general use by man, either in sun bathing or in the use of rays from artificial sources. The incidence of skin cancers in white men is, however, shown to be predelicted to regions of strong sunshine, and it is significant that malignancy is rarely, if ever, seen in negroes. The effective spectral region is shown to be that of 290—334 mμ. Whether there is a specific effect of the radiation, as a formation or photodynamic activation of cancerogenic hydrocarbons, or if the malignancy is developed from chronic, precancerous lesions caused by the repeated irradiation, is still open to question (see BLUM, 1941, 1943, 1945; LAURENS, 1941; HOLLAENDER, 1946). At the present state of knowledge a caution to avoid the frequent excessive exposure to artificial and natural light seems, however, justified (BLUM, 1941).

The Photophthalmia.

The action upon the eye of ultraviolet radiation is of great practical importance. In principle it is similar to the photoerythema, i. e., dependent on a decomposition of cellular proteins. The effect is limited essentially to the cornea and conjunctiva. Depending on the dose, a latent period of several hours is followed by a more or less severe *inflammation of cornea* (*keratitis*) *and conjunctiva* (*conjunctivitis*) with photophobia, copious lacrimation and blepharospasm. The term photophthalmia (PARSON) is used to describe the condition, otherwise known as "snow blindness" and "flash burn" (cf. SCOBEE and GRIFFEY, 1944). The condition is often extremely painful, with sticking pains and a very unpleasant foreign body sensation, but the prognosis is favourable and the symptoms seldom last for more than a day or two.

Radiation of wavelengths about 760—390 mμ penetrates to the retina and is perceived as light. It is the lens of the eye which is chiefly responsible for stopping ultraviolet rays from reaching the retina. The absorption of the cornea begins at about 360 mμ but it transmits down to 295—300 mμ, and about the same is valid for the vitreous and aqueous humors. The absorption in the lens of

wavelengths between about 350 and 400 mμ excites a hazy bluish white fluorescence. Cataract formation by ultraviolet rays is now disputed, and the opacities are probably due chiefly to the presence of the more penetrating infra-red rays in the light sources. The aphakic eye is sensitive to wavelengths as short as 310 mμ, the sensation being blue. The short-wave end of the radiation which can be transmitted to the retina is pushed toward longer wavelengths with increasing age (see, e. g., ELLINGER, 1941; ELLIS, WELLS, and HEYROTH, 1941). According to MIESCHER (1931) the cornea and conjunctiva lack the ability of adaptation to the injurious ultraviolet radiation. The rate of mitoses in the cornea is found to be influenced by ultraviolet radiation and may be used as a sensitive indicator of the radiant effects (see HOLLAENDER, 1946).

The *action spectrum* of photophthalmia is not yet well established. It was known long ago that the effect is chiefly due to wavelengths shorter than about 310 mμ. Recent investigations by FISCHER, VERMEULEN, and EYMERS (1936) and COGAN and KINSEY (1946) will be discussed in the next chapter.

The Antirachitic Effect.

The discovery of the antirachitic effect of ultraviolet radiation, with its later extensions, may be regarded as *the first actual experimental evidence of the importance of sunlight as a factor of bodily health in man.* The stimulation of light research caused by this discovery is clearly demonstrated by the flood of papers which appeared subsequent to 1919 regarding the physiological effects of radiation, and particularly the relation of sunlight to rickets and the production of vitamin D in the skin (see ELLIS, WELLS, and HEYROTH, 1941).

The importance of sunlight for the etiology of rickets was first demonstrated by T. A. PALM in a paper from 1890. He employed the method of geographic survey in the study and noted that the one factor common to all districts where rickets was unknown was sunlight. This view of the etiology is now completely established. Rickets is a disease caused primarily by lack of sunlight; it is a disease of sunless areas, of winter months; a disease caused by artificial conditions which exclude sunlight, such as the massing together of the population in tenement houses and, in the East, of living in purdah (LUCE-CLAUSEN, 1938).

The clinical discovery of the therapeutic effect on rickets of irradiation with the mercury-arc quartz lamp is usually credited to Huldschinsky (1919), although Buchholz apparently cured cases of human rickets with artificial light as early as in 1905. Hess and Unger, in 1921, cured rickets with sunlight and showed that light filtered through a window of ordinary glass was ineffective and that, therefore, only the ultraviolet portion of the solar spectrum was important. The next advance was the demonstration that the light acts by a chemical mechanism. Hess and Weinstock (1922) showed that a section of excised human skin after irradiation by a mercury arc when fed to rats, protected them from a deficient diet, although similar amounts of non-irradiated skin were ineffective. It was thus obvious that an antirachitic substance had been formed photochemically in the irradiated skin. In 1924 Steenbock and associates, and independently Hess, found that antirachitic potency could also be induced in foods by ultraviolet irradiation. The antirachitic material, which was named vitamin D by McCollum in 1925, was found to belong to the sterol fraction of foodstuffs, and the provitamin was in 1927 identified with ergosterol or a hypothetical dehydrocholesterol, present as an impurity in ordinary cholesterol and phytosterols. The provitamin present in the human skin has later been identified as 7-dehydrocholesterol. The vitamin D formed by the action of the ultraviolet rays on the skin is absorbed into the blood stream. Hume, Lucas, and Smith (1927) proved that a protective effect could be produced by rubbing irradiated ergosterol into the skin of rachitic rabbits. The amounts of radiation necessary for the cure of the same rabbits was found to be surprisingly small; an area of skin as small as 2.5 by 3.5 cm irradiated for only ten minutes three times a week was sufficient to produce a normal calcification. Extensive studies on the antirachitic effect of artificial radiation with experimental animals were made by Schultzer (1927). Further investigations on the spectral and dosage dependency of the antirachitic effect of ultraviolet irradiation will be discussed in connection with the design of the ultraviolet-containing illumination system employed in the present investigation.

The definitely proved photochemical synthesis of vitamin D in the skin on irradiation with ultraviolet may be regarded as a direct effect of the radiation, while the effects induced by its absorption

into the blood lead over to *indirect irradiation effects*. There is no possibility of giving more than some fundamental data of different aspects of *vitamin D and mineral metabolism* in this survey; some of the problems will be dealt with more completely in other chapters.

Rickets is a common disease of infants and young children. It involves primarily the growing bones and the teeth and consists chiefly in a failure of calcification of regions where calcium salts are normally deposited during the growth process. This is the result of an inadequate intestinal absorption of calcium and phosphorus present in the diet because of a deficiency of vitamin D in the body. When bodily stores of vitamin D are low, the calcium and phosphorus of the foodstuffs are not absorbed but are lost in the faeces. The disease is usually accompanied by low values of either or both calcium and phosphorus in the blood serum, while the concentration of the enzyme alkaline phosphatase in the blood is increased. General signs of rickets are a catarrh of mucuous membranes, muscular weakness, increased nervous irritability and marked restlessness of the infant; it is however not sufficiently demonstrated that all of these symptoms are due to uncomplicated vitamin D deficiency (Clements, 1946). In some instances, especially when the diet is low in calcium, marked hypocalcaemia occurs, with manifestations of tetany (infantile tetany, spasmophilia).

Modern reviews of the physiological and clinical aspects of mineral metabolism in relation to vitamin D are made by, among others, Shohl (1939), Rominger (1939), Greenberg (1939), Cohn, Cohn, and Aub (1942), Clements (1946) and Bicknell and Prescott (1946). The favoured current hypothesis regarding the mode of action of vitamin D in the body seems to be that vitamin D primarily acts by increasing calcium absorption in the intestine but has no, or but slight, effect on either faecal phosphorus excretion or the absorption of phosphorus, (cf. Greenberg, 1939, 1945). But undoubtedly vitamin D exerts an action in the interior of the body also; it is well established that it increases the metabolic rate. The liberation of inorganic phosphorus from some organic phosphorus compounds seems to be promoted (Räthä et al., 1937; Cohn and Greenberg, 1939). It seems probable that vitamin D involves either directly or indirectly the parathyroid mechanism; the parathyroid glands are hypertrophied in rickets and infantile tetany (cf. Lichtwitz, 1942). A relationship seems reasonable since the latter affects the calcium and the phosphorus metabolism and the cellular mechanism concerned with the growth and destruction of bone. An irradiation product of vitamin D, the dihydrotachysterol, may be used as a substitute for the parathormone (A. T. 10, see Holtz, 1939).

In a chemical sense the name vitamin D identifies a group of some ten sterol compounds, although of these only two have a practical importance. The two are alike in that they represent activated forms of naturally occurring sterols, the latter constituting the *provitamins* of vitamin D. The first is ergosterol, derived from plant sources,

which upon activation becomes vitamin D_2 or calciferol by an internal rearrangement of molecular structure. The second is 7-dehydrocholesterol, a constituent of animal lipids, and is called vitamin D_3 when it undergoes a similar change. The activation is normally effected by ultraviolet radiation of certain wavelengths; in the course of the reaction there is formed a series of compounds, one of which is the vitamin. Irradiation of sufficient intensity and duration may yield toxic substances (cf. p. 56). Cod liver oil, recommended for the cure of rickets by TROUSSEAU in 1822, consists of at least six different forms of vitamin D, the chief of these probably being the 7-dehydrocholesterol form. The ergosterol form is known as viosterol, ultranol, etc. The provitamin present in human skin is predominatly 7-dehydrocholesterol, and the amount of provitamin in the skin is at least 10 and probably 100 times greater than the amount found in the inner parts of the body (see ROSENBERG, 1945).

The antirachitic principle, the vitamin D, is contained in only a few foods in the diet of an average person, namely certain oily fishes and eggs. Muscle meat including the fat, fruit, cereal and vegetables contain none or at the most only traces. The amount in milk is negligible. Liver and butter may contain a small amount but not enough to have any practical value. Summarizing it may be said that, although the diet may occasionally furnish appreciable amounts of vitamin D, most of the time it furnishes virtually none; the only proper attitude is to regard the diet as being completely devoid of the vitamin (PARK, 1940).

The prevalence of rickets is still high in many countries. FOLLIS, JACKSON, ELIOT, and PARK (1943) found by examination of bones from 230 American children between two and fourteen years of age, who died of intercurrent diseases, histological signs of rickets in about half of the material; roentgenologic symptoms were, however, found only in few cases. DUNGAL (1945) reports that 77 per cent of children of Reykjavik exhibit some sign of sustained rickets. In a broad investigation of the average health standard in northern Sweden (Västerbotten and Norrbotten) during the years 1929—1931 it was found that vitamin D deficiency was widely spread among the children (ODIN, 1934), and rachitic changes of the teeth were common (WESTIN, 1934). Clinical evidence of rickets in adults was, however, not found. LANGFELDT (1938) reports that in the northern parts of Norway the supply of vitamin D seems to be secured by the

high content of fish in the diet. In Sweden the exemplary public organization of the prophylactic health control of children up to about 3 years of age has in the last decade considerably reduced the frequency of rickets, and, in fact, cases of rickets in infants are now seldom seen here.

Systemic Effects.

The systemic effects in the body of ultraviolet radiation are primarily regarded as results of the absorption of substances formed by the direct action on the skin, e. g. histamine, H-substance and vitamin D. The penetration of ultraviolet rays into the skin is only 0.1 –1 mm; the longer wavelengths may affect the minute superficial blood vessels directly, some of which are situated at a depth of only 0.3 mm (see LAURENS, 1935; ELLINGER, 1941). Reflexogenic impulses from the skin may be elicited by erythema-effective exposures (v. REIS and SJÖSTRAND, 1938).

The numerous systemic effects associated with exposure to radiation that produces sunburn are difficult to grasp and reduce to brief fundamentals. Sometimes the experimental results are extremely contradictory, which may be due to the fact that some observations have been made on sick, and others on healthy people, and the utilization of different light sources and different dosages has added to the confusion.

Among the effects of ultraviolet radiation on **circulation** the decrease of *blood pressure* is regarded as the most important. In healthy persons, however, the fall of systolic pressure is only about 6 mm and of diastolic pressure 8 mm of Hg (JOHNSON, POLLOCK, MAYERSON, and LAURENS, 1936), and only erythema-effective exposures are active. Carbon arc irradiation is found to be more effective than mercury arc irradiation, which is probably due to the deeper penetration of the longer wavelengths present in the former radiation. The fall of blood pressure is accompanied by an increase of cardiac output and minute volume, which lasts for several days after a single erythema exposure. The pulse may become fuller and stronger during and following a course of irradiations, correlated with increased minute volume. The effect is interpreted as the result of the spreading of vasodilating substances in the body (see LAURENS, 1935, 1938).

The effects of radiation on the **blood picture and haemoglobin level** have been a subject for many contradictory reports (see, e. g., Ellis, Wells, and Heyroth, 1941). One reason for the variations in the results of different observers may be that the primary effect of erythema-active exposures is a vasodilatation followed by a diffusion of tissue fluid into the blood stream, resulting in dilution and increased blood volume (see Mayerson, 1935). Another reason may be that the first effect induced is a haemolysis; it is shown that the excretion of urobilin and stercobilin increases after irradiation (Teplov and Mesheristkaya, 1933; Kasatkin and Bogdanova, 1935). The haemolysis may stimulate to improved regeneration, but if regeneration does not occur the result will be decreased haemoglobin concentration and red blood cell count; such effects are also described.

The results obtained on irradiation of men and experimental animals with artificial sources (carbon and quartz mercury arcs) indicate very little effect on the red blood cell count and haemoglobin content when these levels are normal at the beginning of the investigations (Mayerson, 1935; see also Laurens, 1941). Strong, or long continued, irradiation of individuals with low initial levels results in most cases in a slight rise, seldom averaging more than 10 per cent, in the erythrocyte count, and a concomitant but smaller increase in haemoglobin which is maintained for a longer or shorter time after the irradiation is discontinued. The effect is limited and not specific and far less efficient than dietetic and drug treatment (cf. Handbook of Physical Medicine, 1945).

Long continued darkness produces no marked effect as long as the diet is satisfactory (Laurens, 1938). "Anaemic" looking people in poorly lighted rooms, or in polar regions, etc., in spite of their pallor, often have a surprisingly high haemoglobin content (Mayerson, 1935). Studies made on men on polar expeditions have failed to show specific effects of the long polar night. The seasonal variation of the haemoglobin content, with the highest values in summer, first reported by Finsen in 1894, seems to be less pronounced now (cf. Andersen and Normann, 1948). It seems probable that other factors, nutritional or otherwise, are responsible for this variation, rather than the lack of radiation (cf. p. 115).

On the other hand, light undoubtedly exercises some effect on the *blood picture.* An increase of the reticulocyte count following

artificial irradiation and also appearing in spring has been frequently described, as well as a spring eosinophilia (see DE RUDDER, 1938). Leukocytosis, and particularly lymphocytosis, results from moderate irradiation but markedly low values in the white blood cell counts may follow excessive exposures (MAYERSON, 1935; cf. HEINILD, 1944). The results seem consistent in demonstrating a definite and sustained rise in the number of thrombocytes in man and animals on ultraviolet irradiation (MAYERSON, 1935; cf. ELLINGER, 1941).

The influence of ultraviolet radiation on **metabolism** offers a field containing a great number of observations. When the effects on the mineral metabolism directly or indirectly dependent on the formation of vitamin D are excluded, only a few observations may be regarded as significant.

An intensified protein breakdown is reported with increased nitrogen, sulphur and phosphorus excretion, which is considered to be a sign of the cell destruction indicated by the erythema (see ELLINGER, 1941). Both artificial and natural solar radiation causes a lowering of the blood sugar in normal men and especially in diabetics; the action is said to be similar to that of insulin inasmuch as the glycogen content of the liver and muscle increases (see LAURENS, 1941; ELLINGER, 1941). The fat and cholesterol content in blood may increase (see LAURENS, 1938).

LEHMANN and SZAKÁLL (1932 a) made an extensive study of the influence of ultraviolet irradiation on the *work and rest metabolism and the working capacity* of a group of men. Brief intense irradiation, producing an erythema, was found to lead to an increase in metabolic rate lasting for as long as 22 hours. Repeated irradiation produced a diminution of between 10 to 15 per cent in basal rate, demonstrable for 3 to 4 weeks after the last irradiation. There was a parallel increase of the respiratory quotient, which rose from 0.75—0.85 to more than 1.0. This signifies that a preferential combustion of carbohydrates follows the irradiation (cf. above). The effect on respiration was to make it easier, slower and deeper, and the pulse rate was decreased. These effects on the rest metabolism are apparently reminiscent of the effects normally occurring during a course of physical training. A marked improvement of the *working metabolism* was also found following the series of irradiations; the maximal working capacity was increased, the mechanical efficiency

markedly improved (up to 60 per cent) and the pulse rate was lowered and returned more rapidly to normal level after exercise. In a later series of the investigation, a group of men was irradiated in the same way but with the radiation filtered through ordinary window glass. None of the effects described above were then obtained; hence, the effects may not be ascribed to psychological influences, and only ultraviolet radiation of wavelengths below 320 mμ is effective (Lehmann and Szakáll, 1932 b).

The *improvement of physical fitness* indicated by these studies following on ultraviolet irradiation has been supported by later investigations. Moschkowsky (1936) found that the run of 11 km in one hour was performed with less ventilation and oxygen consumption even after the first ultraviolet irradiation; the effect lasted for about 10 days and was also produced after irradiation of only the face and shoulders. Parade and Otto (1939) found that the accumulation of lactic acid in the blood during work was considerably decreased after irradiation; they ascribe the effect to the activation of vitamin D which is assumed to act by means of the adrenal cortex. Lehmann and Szakáll (1944), in a repeated study, confirmed their previous results by employing different fitness tests, one of which has been applied in the present investigation also (see Chap. 11). They found no effect of irradiation exposures below the erythema threshold and ascribe the effect of radiation as due to erythema substances liberated from the skin. Finally, Allen and Cureton (1945) studied motor and cardiovascular fitness in two groups of college freshmen, one of which received regular doses of ultraviolet irradiation. Both groups were given regular physical training. Muscle endurance tests, the Schneider test and the Schneider index rating were used for the comparison, and the experimental group showed significantly higher standard score gains than the control group in all the tests.

The influence of radiation on **growth** is a problem, in which relatively little well controlled work has been done on man. Studies on lower animals have, as a general rule, shown that radiation has only a negligible influence on the growth and development of mammals fed with adequate and complete diets. All results are consistent in showing that rats reared on an optimal diet grow as well in darkness as in well-lighted rooms, and that irradiation with the quartz

mercury arc has no demonstrable effect unless massive exposures are used, in which case there may be an inhibition of growth (see MAYERSON, 1935).

NYLIN (1929) studied the growth of a large number of Swedish pre-school and school children and found periodic variations during the year. The height increase was pronounced during the summer and showed two maxima: a marked maximum during March and April and a smaller but distinct maximum during November and December. The minimum height increases occurred during September and October and January and February. In general, weight increase varied inversely with height increase. Two groups of 25 boys each were irradiated at different times in winter for periods of two months or more with quartz mercury arcs supplemented with "Sollux" lamps for providing long-wave radiation. The average increases in height of the irradiated groups were found significantly greater than those of the controls. NYLIN attempts to correlate the periodicities in growth with the known seasonal variations in ultraviolet radiation, but it proved difficult on this basis to account for the distinct maximum in December.

Regarding, at least, the effect of ultraviolet radiation on **resistance to infection** a survey of the literature reveals the most contradictory opinions. Claims are persistently made for such an effect by manufactures as well as by members of the medical profession, in spite of *most of the well controlled investigations definitely showing no effect at all.* The same is the case for vitamin D treatment (see SCHNEIDER, 1946). COLEBROOK (1929, 1946), commissioned by the British Medical Research Council, has made two authoritative large-scale investigations on artificial sunlight treatment, the first one (1929) dealing with irradiation of school children and the other (1946) with industrial and office workers (for a review of the literature see COLEBROOK, 1946). Besides the irradiated group and the control group there has also been in both trials a group receiving only the ultraviolet rays transmitted by ordinary window glass, i. e., with wavelengths below about 320 mμ screened off. In the school-children investigation, each of the three groups consisted of 100 children, and the irradiation was applied with quartz mercury arcs during the period September—March. Full erythema doses were given 3 times a week. There was no significant influence of the irra-

diation on either the weight and height increases, the incidence and duration of colds or other diseases, or on the progress of school works. Hill and Laurie (1931) repeated her investigation, using 400 children between 9 and 12 years of age, divided into four groups, the one of which was given 2 exposures to the carbon arc weekly with doses only one tenth of those employed by Colebrook. By means of special clinical points, referring to weight, tonsils, conjunctiva, appetite, sleep, colds, etc., they demonstrated a definite favourable influence of the irradiation. They attributed the negative findings of Colebrook to "over-irradiation" of the children. An American investigation in the same years on 179 students failed completely to show any favourable effect in diminishing the annual number of colds (Doull, Hardy, Clark, and Herman, 1931). The recent trial of Colebrook (1946) comprised 3,000 office, factory, and colliery workers in three communities. One group received the full range of ultraviolet radiation from quartz mercury-arc lamps, given as minimum perceptible erythema doses, while another group received irradiation with the shorter ultraviolet rays screened off; a control group received no treatment at all. The results of the experiment, covering most of the winter months, give no evidence of artificial sunlight treatment being effective in reducing the incidence of sickness and accident. Kovács (1947), in a discussion of these negative results, attributes them to "the fact that the minimum perceptible erythema dose is insufficient to produce therapeutic results", and recommends the use of higher dosages.

CHAPTER 3.

Hygienic Applications of Ultraviolet Radiation.

The therapeutic use of ultraviolet radiation was scientifically founded by Niels R. Finsen in Denmark at the turn of the century, and was developed by, among others, Bernhard and Rollier in Switzerland and Sir Henry Gauvain in England. The hygienic applications of ultraviolet energy, on the other hand, arose from the discovery of its antirachitic properties and the relation to vitamin D, made in the nineteen-twenties (Huldschinsky, Hess, Steen-

BOCK, and others). An overwhelming interest developed, culminating in the nineteen-thirties. In recent years interest has again been focussed on the hygienic aspects of ultraviolet radiation and now mainly on its bactericidal properties. The pioneer of this special application of ultraviolet energy has been W. F. WELLS in the U. S. A.

Ultraviolet Radiation for Interiors.

The first trend in the early period was to utilize the daylight and sunlight content of ultraviolet energy also in the illumination of interiors. It was well-known that ordinary window glass is almost completely opaque to the antirachitic wavelengths, and in 1926 the first *ultraviolet-transmitting glass* manufactured on a large scale appeared on the market in England ("Vitaglass") and was followed by a number of other such glasses, (see ELLIS, WELLS, and HEYROTH, 1941). A simple and practical window for transmitting ultraviolet rays may be obtained by using cellophane (PFUND, 1928). The ineffectivity of such arrangements for general use was, however, soon made apparent; there is comparatively little of the valuable ultraviolet in the sunlight during the winter months, and the fraction of daylight entering a room through an ordinary sized window is very small (CLARK, 1928; KOLLATH, 1929). CLARK estimated that a person would receive as much ultraviolet radiation in two minutes in direct sunlight at noon "when out for lunch", as in an entire day at 5 meters behind a window of ultraviolet-transmitting glass exposed to the north sky. In special cases, as for balconies or sky-lighted rest rooms, ultraviolet-transmitting glass may, however, be of some value. The ultraviolet transmission of these glasses decreases considerably during use (see KOCH and WIDMARK, 1928).

The next step to an improvement of the indoor radiation conditions was the proposal to utilize *artificial ultraviolet sources for the general illumination of interiors* (LUCKIESH, 1930). Special sources were developed for this "dual-purpose lighting" at the GENERAL ELECTRIC, U. S. A. (the S-1 and S-2 sun-lamps, and others, see p. 17). Fundamental design data were presented regarding equipment to control the distribution of ultraviolet, and recommendations were made regarding the installation of such equipment for various classes of interiors (PORTER, EGELER, and STURROCK, 1932). The ultraviolet lamp was usually placed in ceiling reflectors giving di-

rect radiation, while the incandescent lamps used to produce illumination were equipped with indirect or semi-indirect units. Oday and Porter (1933) describe a number of such installations in different localities, as offices, hospitals, swimming pools, and other public rooms. Fixtures were arranged for the continuous burning of both sources at one time, or so that the ultraviolet or general illumination sources could be used separately. The indirect distribution of ultraviolet radiation by means of ultraviolet-reflecting paints on the ceilings was suggested as promising. It was recommended to choose the ultraviolet sources so that only very mild irradiation was produced when combined with the general illumination. The erythemal response was the basis for the design, and about 1/10th of the erythema dosage was recommended as a suitable daily exposure.

The Ultraviolet Committee (No. 41) of the International Commission on Illumination has presented an extensive discussion on those exigencies which should be met by an 'ultraviolet illumination' (I. C. I., 1937, 1942), and frequent references will be given to their reports and reviews in later chapters. The present state of the technical features of producing artificial sunlight is reviewed by Krefft (1942 a) and Luckiesh (1946). The best practice at the present time would be a lighting installation of fluorescent lamps supplemented with mercury-arc sun-lamps (Luckiesh), but most recent reports seem promising for the use of fluorescent "sun-tan lamps" (Clapp and Ginther, 1947). No experimental data, however, have appeared regarding the possible hygienic and physiological value for man of such installations for ultraviolet illumination.

The common sources for general illumination of interiors only radiate small intensities in the ultraviolet spectral range. An ordinary illumination by incandescent lamps, even with bare lamps, cannot prevent rickets in rats fed on rachitogenic diet, while a moderate level of illumination from bare mercury lamps for artificial lighting, with bulbs of ordinary glass, exerts a slight protecting and healing effect. This effect is completely spoiled if the lamps are placed in usual globes of opal glass (Ronge, 1945). Some types of fluorescent lamps have been shown to increase the calcification of the bones of chickens (Willegroth and Fritz, 1944, see Fritz, 1945). A comparison between the radiant energy from fluorescent lamps and the radiant energy in sunlight and skylight is recently given by Luckiesh and Taylor (1945).

Mörikofer (1931) has made a detailed investigation on the permeability of various *clothing materials* to ultraviolet rays. The whipcord fabrics chiefly used for men's clothing are practically impermeable to ultraviolet radiation, while

materials such as cotton voile, silk stockings and cotton stockings may transmit 18—40 per cent. It is demonstrated that the weave (pore-size) is more important for ultraviolet permeability than the absorption of rays by the fibres.

Artificial Sunlight Treatments.

The collective irradiation of industrial and office workers, miners, school children, etc., is the common form for the administration of artificial sunlight treatment on a public scale. There are usually no special difficulties to arrange such treatment even for large numbers of people; the common arrangement in industries is by means of special irradiation chambers, "solaria", connected with washrooms or other sanitary facilities of the plant (see, e. g., MEYER and SEITZ, 1942). Further attention to the general hygienic potentialities of such treatments has been stimulated by the increased use of artificial lighting in workplaces and the black-out conditions during the war years.

The main interest for both the medical profession and the general public is the possibility of *promoting and maintaining health* by means of such treatments. In spite of the numbers of trials and inquiries made on this basic problem it is at present difficult to give an impartial judgement in the case; this may indicate that the possible benefits are not very pronounced and clear cut. There are at least two reasons which have made the scientific interpretation of the results so dubious. The first refers to the influences of *psychological factors*; the treatment is well-known to the public and enjoys a widespread reputation, resting on claims of both subjective and objective benefits. Both the investigator and the subjects may be prejudiced either for or against it, which may influence the interpretation. The second reason is obviously the inherent difficulties in obtaining an *objective measure of health-improvement* in an ordinary "healthy" population. Different attempts may be made to this end. The continuous record of the incidence and duration of illness, primarily colds, has been the most common method. Another estimate may be obtained by questionnaires on the subjective opinions of the effects of the treatment. A third measure of "health-improvement" may be attained by the application of special physiological or psychological tests which are likely to be related in some way with a good physical and mental condition.

In the light of these considerations the present state of the situation may be interpreted in the following way. The results regarding an effect on the *incidence and duration of illness* (*colds*) seem highly contradictory, but a critical review indicates very little evidence that these benefits really are produced by irradiation (COLEBROOK, 1946); anyhow, it seems to be very difficult to find the form of administration which will guarantee a favourable effect in this respect (cf. p. 35).

The opinion of the subjects themselves regarding the effects of the irradiation has been consistently in favour of the treatment; the recent trial of COLEBROOK showed that all the subjects enjoyed the treatment, and about one third of the volunteers who remained to the end of the course felt better, a few much better. The favourable impressions were in all trials prevalent among the good attenders of the course. A noticeable observation was that the subjective opinions did not differ appreciably as between the unscreened and screened lamp groups, i. e., there was no evidence of a specific effect of wavelengths below about 320 mμ. The prejudice of the subject may of course be a dominant factor for his opinion of the treatment, but some value must however be placed on it. The use of the treatment might be justified on account of subjective effects alone (COLEBROOK, 1946).

The third method stated above for approaching an objective measure on a general health-improvement, namely by means of special *physiological and psychological tests* on physical and mental condition, has not yet been applied to any great extent. The experiments of LEHMANN and SZAKÁLL (1932, 1944) on the effect of irradiation on working metabolism and capacity, supported by all subsequent investigators (see p. 33), may be referred to this category of tests. It seems conclusively proved that ultraviolet irradiation produces a metabolic effect in the body which appears to be similar to that produced by physical training, and is followed also by an objectively estimable improvement of physical fitness. It seems likely that the "tonic" properties generally ascribed to both natural and artificial sunlight treatments to some degree can be explained by this metabolic effect of the ultraviolet rays. Further experiments on this line seem to be a promising method of studying the general radiation effects on man.

It must be pointed out, however, that the artificial sunlight treat-

ment is only a poor substitute for natural sunbathing; the latter includes not merely a question of radiation, but of radiation, fresh air, wind, temperature, humidity, etc., and it is most often connected with pleasant and enjoying activities as water bathing and work and play in a minimum of clothing. The action of these factors in the production of benefits from an out-of-door life may not be disregarded. Sunlight is only one of the many environmental factors that affect vitality.

Disinfection by Ultraviolet Radiation.

The discovery of the lethal effect on bacteria of radiation, made in 1877 by Downes and Blunt, first called attention to the importance of radiation in biology (see Clark, 1939). Much information was collected on this effect during the early history of photobiology (see Winterstein, 1931; Ellis, Wells, and Heyroth, 1941), among which may be mentioned the observation of S. Bang, made in Finsen's laboratory 1905, that the bactericidal effect increases sharply as the wavelengths employed are decreased.

The important relation of bactericidal effect to the exposure to different wavelengths was later carefully studied by, among others, Gates (1929). The *action spectrum* obtained in this work shows a maximum around 265 mμ, while the effect at wavelengths above 300 mμ was comparatively small. The reciprocity law was found to hold over a fairly wide range from a fraction of a second to several minutes exposure. The deviations occurring are most marked with young organisms, metabolically and genetically active. Practically all investigators who have determined the wavelength dependence curves for the killing of bacteria have found them to be more or less of the same shape. The sensitivity of bacteria is decreasing from the maximum at 265 mμ to a minimum around 230 mμ, beyond which it rises again. The energy necessary to kill bacteria at longer wavelengths, e. g., 365 mμ, is 1,000 to 10,000 times the energy necessary at the wavelength 265 mμ. Some bactericidal effect is produced also by visible radiation (see Hollaender, 1942, 1946; Buchbinder, 1942). Influenza virus is found to have about the same sensitivity curve as bacteria, while other viruses show a steadily increasing sensitivity toward shorter wavelengths (Hollaender and Oliphant, 1944).

It is only in comparatively recent times that attempts have been made to utilize the bactericidal properties of ultraviolet radiation for the practical sterilization of foods, drugs, water and air. Among these applications the *air disinfection* has proved to be effective in reducing air-borne spread of disease, while the method has definite limitations for most of the other purposes; it is mainly restricted to surface sterilization of foods and sterilization of certain pharmaceutical preparations.

The importance of air as a vehicle for the spread of infectious agents, conceived a long time ago, was proved by W. F. Wells in 1933 (see Wells and Wells, 1936, 1942). The new hypothesis developed on "*air-borne infection*" postulates that the greatest spread of respiratory infections is produced by small dried droplets floating in the air for relatively long times and distances, or by the resuspension of dried droplets in air after they have settled to surfaces such as floors, clothing, and bed clothes (see Moulton, 1942). These "droplet nuclei" constitute the dried residues of infected droplets formed in the liquid spray from coughs and sneezes. The vulnerability of these air-borne microorganisms to ultraviolet radiation was offered as a basis for sanitary control of air-borne infections by W. F. Wells in 1935 (see Wells, Wells, and Wilder, 1942). The low-pressure mercury arc generates primarily ultraviolet radiation of the wavelength 253.7 mμ (see p. 18), which is in close agreement with the maximum of sensitivity of bacteria. Enclosed in tubes or bulbs of clear ultraviolettransmitting glass it is an effective source for the radiant air-disinfection (see Council on Physical Medicine, U. S. A., 1943; Coblentz, 1945 a).

The general principle for the installation and operation of these bactericidal lamps for air-disinfection is the *irradiation of the air above eye-level* in the room. The intensity in the occupied zone of the room must be very small owing to the strong photophthalmia and erythema effectivity of this short-wave ultraviolet radiation. By suitable selection and installation of bactericidal fixtures the irradiated stratum of the air can be almost completely sterilized, and the local interchange of air between the upper and lower levels may provide a "sanitary ventilation" in the occupied zone with a reduction of the concentration of bacteria.

The early experiences regarding the efficiency of radiant air-disinfection in preventing the spread of respiratory diseases in different

localities, as hospital wards, children's hospitals, schools, etc., are collected in the volume Aerobiology, published by MOULTON (1942), together with a number of basic papers in the field. Recent experiences are briefly reviewed by HOLLAENDER (1946). It seems proved that upper-air irradiation with high intensity bactericidal lamps *is of definite value in reducing the incidence of respiratory illness in certain localities;* in a well controlled experiment carried out in a naval training centre with irradiation in the barracks the reduction of respiratory infections was estimated to be 25 per cent (WHEELER et al., 1945). It seems probable that this method of sanitary improvement will find many suitable applications.

Conclusions for the Present Investigation.

The survey given in previous chapters of the biological effects and hygienic applications of ultraviolet radiation indicates that a general, low-intensity ultraviolet irradiation of occupied rooms may possess hygienic potentialities both with respect to direct action on the occupants and bactericidal action on the air and surfaces of the room. Such an irradiation, connected with the artificial illumination system, was to be employed in the present investigation.

The general planning involves two features, in the first place, the *basic design and technical arrangement* of the ultraviolet-illumination system, and in the second place studies on the *physiological and hygienic effects* of this kind of illumination. A comparison between the artificially produced radiation climate in the experimental rooms and the *natural outdoor radiation climate* at different seasons and latitudes forms an intermediate section of the investigation.

Among the direct effects upon the occupants it is primarily the possible influences on the *mineral metabolism* and the *physical fitness* which are of interest. For both of these functions of the body ultraviolet radiation is proved to be a potential factor; to what extent it is an essential factor is not yet established. This may be evaluated by studying the influence of natural ultraviolet radiation as it is manifested by seasonal variations, and by studying the influence of an artificial supply of radiation during seasons when the natural supply is reduced.

The hygienic potentiality with respect to the bactericidal effect

of ultraviolet radiation may be studied by the *reduction of bacterial density* produced by the irradiation, and by the *reduction of respiratory, air-borne infections* which may result from this.

The extent to which these conclusions are justified may be gathered from the results of the present investigation as given in following chapters.

II.

The UV-Illumination System.

CHAPTER 4.

Dosimetric Principles and Basic Design.

For the design of an illumination system with the dual purpose of providing visual illumination and ultraviolet irradiation the prototype given *a priori* is of course the natural daylight. It is, however, of fundamental importance to realize the great difference between the ways visible radiation and ultraviolet radiation act on human beings. *The visual effect*, i. e., the seeing, is primarily related to the *intensity of light*, but in such a manner that common visual tasks can be performed at much lower intensities than those prevalent in average outdoor daylight. One of the reasons is that the response of the eye to visual stimulation is — according to the law of WEBER — approximately proportional to the logarithmic increase, or decrease, of the intensity; a depletion of the illumination from 100,000 lux in sunshine to 10,000 lux in shadow is not perceived to be greater than from 1,000 lux in indoor daylight to 100 lux in indoor artificial light, in spite of the differences being in the first case 90,000 lux and in the second case 900 lux. To this logarithmic response the great power of adaptation of the retina is further added. *The ultraviolet irradiation effects*, on the other hand, are all of slow photochemical origin and then — according to the law of BUNSEN and ROSCOE — the *amount of radiation, i. e., the dosage*, is the factor determining the biological effect. A time factor is entering, as dosage equals the product of intensity and time of exposure; the surface area exposed may also sometimes be taken into account.

A consequence of this is that an approvable artificial radiation climate must not necessarily contain as much visible light as daylight in order to give satisfactory seeing conditions, but it must contain exactly the same ultraviolet intensity in order to give the same photobiological effects in the same time. A *similarity with sunlight* with regard to the relative spectral proportions of ultraviolet

and visible radiation may not be pursued, as the two components act according to different laws. The average, total sky light is in these respects a better prototype, as the ultraviolet intensity at least is as high as in direct sunlight, the light intensity however being only about 1/10th of that of sunshine (see Chap. 8).

The design of the *illumination component* of the system has thus only to be concerned with the intensity of light with respect to the visual tasks to be performed, and with some respect to the colour of the resultant light, while the *irradiation design* must include the dosage of radiation on the occupants with respect to a number of different biological responses. From this latter dosimetric point of view it is suitable to separate, at first, the following three direct effects of ultraviolet radiation on man:

the erythema and pigmentation of the skin,
the inflammation of the cornea, (photophthalmia), and
the antirachitic effect.

To these effects on the occupants an environmental effect of possible hygienic importance must be added:

the bactericidal effect.

The purpose of the design is to evaluate the spectral composition and the irradiation intensity of the ultraviolet component, which produces the effects desired but eliminates any harmful effect. To the first category must be referred, in the first place, the antirachitic effect on the occupants and the bactericidal effect on the environment, especially the air. A moderate erythemal and tanning effect of the illumination may also be considered of some value, but with regard to the small skin area exposed much systemic effect in the body is not to be expected from this. The harmful effect to be primarily avoided in the illumination is obviously the eye-irritation (photophthalmia), and the use of protecting eye-glasses may be out of question.

The experiments on the possible physiological and hygienic effects of such an ultraviolet-containing illumination (UV-illumination) were planned to be carried out on school children with the irradiation applied during their stay in the school. The classrooms were thus the localities which should be provided with the UV-illumination system. The time-table of the classes selected was almost constant for all days

and the stay of the children in the classrooms could reach about 5 hours. Artificial illumination was needed for at least 2—3 hours of the ordinary school day during the darkest winter months. From the experimental point of view it was considered suitable to apply *the daily ultraviolet exposure as high as possible*, the upper limits primarily consisting of the photophthalmia and the photoerythema. This was the actual basis for the dosimetric design, and the procedure employed to lead from this to the choice of a suitable source for the UV-illumination will be described below.

The Evaluation of Effective Radiation.

Different parts of the ultraviolet spectrum vary with regard to their efficiencies for producing the photobiological effects stated above. This wavelength dependence is expressed by the *action spectrum* of the response, and it corresponds, in the main, to the absorption spectrum of the substance responsible for the effect (law of Grotthus and Draper). The degree of response is ultimately determined by the amount of active radiation absorbed during the exposure and then depends on the spectral intensities of the radiation and the time of the exposure. The best measure of the potential power which a given radiation possesses for producing a biological effect is obtained by multiplying, for each wavelength, the spectral intensity with the corresponding efficiency factor. The sum of these *weighted spectral intensities* gives the measure of the power expressed as the equivalent intensity of the reference wavelength, i. e., the wavelength of unit efficiency. This fundamental procedure to obtain a numerical measure on biologically-effective radiation may be summarized in the formula

$$E = \int_{\lambda_1}^{\lambda_2} I_\lambda \, V_\lambda \, d\lambda$$

where

E = the obtained, weighted intensity,

I_λ = the intensity and V_λ = the efficiency factor of the wavelength λ, and

λ_1 and λ_2 = the wavelength limits of the action spectrum.

The principle is further illustrated in fig. 3.

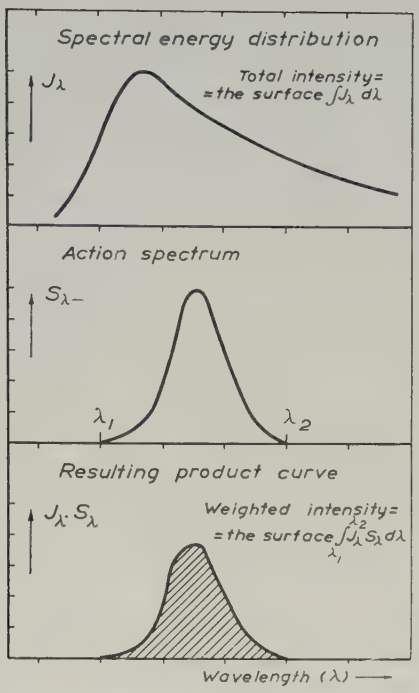

Fig. 3. The principle of evaluating radiant energy in terms of weighted units.

The physiological radiation units obtained in this way correspond in principle to the common *units for visible radiation*, i. e., lumen as the measure of luminous flux, and lux[1] as the measure of luminous intensity. The action spectrum is in this case the spectral luminosity function of the eye, with the reference wavelength 555 mμ (see fig. 1). By means of the mechanical equivalent of light, equal to 650 lumen/watt, a given luminous flux may be transformed into the equivalent flux of homogeneous radiation of the wavelength 555 mμ, measured in physical (absolute) units. In designing an irradiation system like the present one it is as suitable, or necessary to use such weighted physiological radiation units as it is to use lumen and lux in designing illumination systems.

The basic supposition for obtaining reliable measures of the biological effectivity of a radiation by such weighted units is obviously an exact knowledge of the action spectra. In this respect the best

[1] 1 foot-candle = 10.76 lux.

known is the threshold erythemal response of untanned human skin, and for the antirachitic effect as well as the germicidal effect the data available permit at least a rough estimate of the spectral efficiencies. Less known, unfortunately, is the spectral response curve of the photo-inflammation of the eye. A detailed account of the data will be given below, but first the units and terms employed must be described.

The Units and Terms Employed.

A general proposal of a nomenclature and standards for biologically effective radiation was given by Luckiesh and Holladay (1931 b, 1933), who introduced the term *viton* for radiation spectrally weighted by the respective efficiency factors of each wavelength (cf. Luckiesh, 1946). The erythemal viton (E-viton) has been standardized by the Illuminating Engineering Society, U. S. A. (1933, 1935), as a term and also as a quantity equal to 10 μW of erythemal flux, i. e., 10 μW of radiation after being erythemally weighted and, consequently, is equivalent to 10 μW of erythemal energy of the wavelength of maximal erythemal effectivity (296.7 mμ). The corresponding unit for erythemal flux density (intensity) is the *Finsen*, defined as one viton per cm^2. This system is, however, not generally adopted and many objections have been raised (Schulze, 1935; I. C. I., 1937, 1942). The Council on Physical Medicine, U. S. A., (see Coblentz, 1945), has adopted the term Erythemal Unit (E. U.) of dosage intensity, equal to 10 $\mu W/cm^2$ of homogeneous radiation of the wavelength 296.7 mμ.

For germicidal energy Luckiesh (1946) proposes a unit G-viton as being equivalent to one mW or μW of radiant power of maximal germicidal effectivity (stated by him to be 253.7 mμ), and a Germicidal Unit (G. U.) of exposure as being equivalent in germicidal effectivity to one microwatt of the wavelength 253.7 mμ incident upon a projected area of one cm^2 for a period of one minute.

A consistent application of the idea of introducing special units as exemplified above for all the different ultraviolet irradiation effects would obviously lead to a rather complicated system. It should be emphasized that there are two different questions to be distinguished in the formulation of such biological radiation units: the one is to have a *term* for the biologically-weighted radiation, the other is to standardize a *unit* for it — with respect to both radiant flux, radiant intensity and radiant dosage. Considering the great number of different irradiation effects, each with quite different action spectra and threshold dosages, it seems reasonable to restrict the new definitions required to a term for the weighted radiation only, and not to standardize any special units for the amount of such

radiation. The quantitative data are more clearly expressed in ordinary physical units, conveniently watts or decimals of watts, and the dimension immediately gives the meaning of the datum. Thus, for instance, radiant flux must always be given in watts (or decimals thereof), radiant intensity in watts per unit area, radiant dosage in watt-seconds or watt-seconds per unit area (the latter giving the intensity of the exposure).

In the present study the terms necessary for expressing *radiant energy weighted by an action spectrum are replaced by brief symbols*, as, for instance, UVE for erythemally-weighted radiation and UVG for germicidally-weighted radiation. Erythemal flux is expressed by, e. g., mW of UVE, erythemal dosage by mWsec/cm² of UVE and so on. This system of nomenclature is related to the classification of the ultraviolet spectrum once proposed by Coblentz, by which the spectral range 400—315 mμ is termed UVA, the range 315 –280 mμ UVB and the range below 280 mμ is termed UVC. This classification has been widely applied in European literature but is not generally adopted in the U. S. A. (cf. Meyer and Seitz, 1942).

In dealing with *quantitative data of biologically-weighted radiation*, on the other hand, any possible biological unit ought to be related to the threshold dosage of the response in regard or to any other fixed degree of response. A threshold value may be expressed in, e. g., mWsec/cm² of weighted radiation, as in the case of the erythema response, the ophthalmia response, and the yield of vitamin D per unit area of skin. An expression for the power of an ultraviolet source in each of these respects may simply be obtained by dividing the weighted flux totally emitted (in mW) by the corresponding threshold value (in mWsec/cm²), the quotient cm²/sec thus giving *the area which in one second would be brought up to the threshold response if all the radiant flux were concentrated on it.* These quotients, or power-values, include the advantage of being numerically directly comparable. Thus, if the figure of the erythema power (UVE-power) is greater than that of the ophthalmia power (UVK-power) it is indicated that the irradiation of the face with unscreened eyes will produce photophthalmia before skin erythema, and in the same way the yield of vitamin D per unit area of skin may be seen in relation to the simultaneous erythemal response, and so on. For an ultraviolet point source with spherical intensity distribution curve the quotient

$$\frac{4 \cdot \pi \cdot 10{,}000}{\text{power value}}$$

gives the time in seconds necessary for producing a threshold response at a distance of one meter from the source. The efficiency of the source with respect to different biological effects may be expressed as power-value per watt input energy.

It must, however, be strongly pointed out that the basis for such a system of biological units of radiant power is provided by two main suppositions which are not generally valid. In the first place the threshold dosage of a response is not a universal constant but varying considerably for different individuals, different skin areas, different seasons, etc. Secondly, the reciprocity law of the photobiological response is valid only within certain limits, i. e., a given dosage applied with low intensity during a long exposure may fail to produce the effect which should have been produced by the same dosage applied during a short exposure. In spite of these objections, however, this manner of biological rating of ultraviolet sources is found practicable in calculations and design of the irradiation system connected with the artificial illumination. Practical applications are given on later pages.

Latarjet (1944, see Kovács, 1947) has proposed a unit sterilizing dose and a unit erythema dose (Finsen) of ultraviolet radiation, which are based on the same principles as applied here.

Dosimetric Relations of the Ultraviolet Irradiation Effects.

The Photoerythema and Photopigmentation.

The action spectrum of the photoerythema has been the subject a number of investigations. The first exact study was made by Hausser and Vahle (1921, 1928, see K. W. Hausser, 1934) and their results have been supported, in the main, by the later investigations (Luckiesh, Holladay, and Taylor, 1930; Adams, Barnes, and Forsythe, 1931; Coblentz, Stair, and Hogue, 1932). The Illuminating Engineering Society, U. S. A., accepted (1933, 1935) an action curve based on an interpretation of the available data by Coblentz and Stair (1934), and the same curve was adopted by

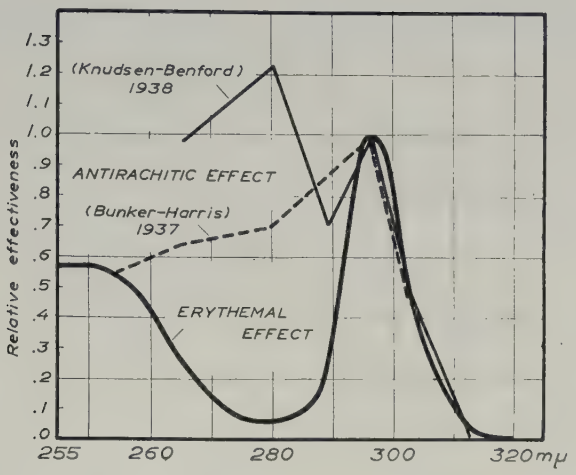

Fig. 4. Action spectra of the photoerythema and the antirachitic effect. The relative action factor for the wavelength 297 mμ is taken as unity for all spectra.

the International Commission on Illumination in 1935 (I. C. I., 1937). The curve is shown in fig. 4, and the relative erythemal factors of the wavelengths of the mercury spectrum are given in Table 1. This is the curve applied in the present investigation for the evaluation of the weighted radiation termed UVE. It should be pointed out that the curve is valid only for the threshold erythemal response; for higher degrees of erythema the curve is modified (Adams, Barnes, and Forsythe, 1931).

In the main, the photochemical processes underlying the erythema and pigmentation responses of the skin on ultraviolet radiation are rather well understood (for literature see Chap. 2). The erythemal, inflammatory response is limited to wavelengths below about 315 mμ, while the *pigmentation (tanning) effect* is caused by the long-wave ultraviolet above 315 mμ, with the maximum efficiency in the region 340—880 mμ. A brownish pigmentation of long duration is produced by these longer wavelengths without preceeding erythema (Lomholt, 1936; I. Hausser, 1938). The direct pigmentation requires considerably more energy than the production of erythema by the shorter wavelengths; the threshold value of a pigmentation by 365 mμ is 500—1,000 times the threshold value of the erythema by 297 mμ. Thus, *the pigmentation following exposure to ultraviolet radiation mainly depends on the prevalence of high intensities of long-wave ultra-*

Table 1. *Relative Action Factors of the Mercury Spectral Lines for Producing Biological Effects.*

Effect	Erythema	Photophthalmia		Antirachitic effect		Germicidal effect
According to	I. C. I., 1935	Cogan and Kinsey, 1946	Fischer, Vermeulen, and Eymers, 1936	Knudson and Benford, 1938	Bunker and Harris, 1937	Hollaender 1942
Wavelength, mμ						
313	0.03	0.02[1]	0.02[1]	0.01	0.0	0.01[1]
303	0.55	0.13	0.05	0.39	0.47	0.05[1]
297	**1.00**	0.45	0.10	0.81	**1.00**	0.27
293	0.70	0.75[1]	0.16[1]	0.65[1]	0.92[1]	0.38[1]
289	0.25	**1.00**	0.22[1]	0.57	0.87[1]	0.46[1]
280	0.06	0.37	0.36[1]	**1.00**	0.70	0.70
275	0.07	0.35[1]	0.45	0.92[1]	0.68[1]	0.80[1]
270	0.14	0.32[1]	0.55[1]	0.85[1]	0.66[1]	0.90[1]
265	0.25	0.30	0.66[1]	0.79	0.64	**1.00**
257	0.49	0.27[1]	0.82[1]		0.58[1]	0.80[1]
254	0.55	0.25	0.89[1]		0.54	0.70
248	0.57	0.22[1]	**1.00**			0.50[1]
245	0.57	0.20	1.00[1]			
Threshold dose of weighted radiation mWsec/cm²	20[2]	20[3]	4[3]	23[4]	13[4]	0.3[5] (50 mWmin/m²)
Symbol used for weighted radiation	UVE	UVK	UVX	(UVD)		UVG

[1] Interpolated value.
[2] Human, unpigmented skin.
[3] Rabbit eye.
[4] Per 1 I.U. vitamin D in rat skin.
[5] For unit lethal exposure (36.8 % survival) of *E. Coli*.

violet in the spectrum. The quartz mercury arc radiation is rather weak in the tanning-effective spectral region as compared with both sunlight and carbon arc radiation (see fig. 20, p. 89).

The *threshold dosage of erythema* has been estimated in connection with most of the investigations carried out on the action spectrum. Hausser and Gauer (see K. W. Hausser, 1934) found values about 36 mWsec/cm², Coblentz, Stair, and Hogue (1932) values about

50 mWsec/cm², and Luckiesh, Holladay, and Taylor (1930) give the mean threshold dosage as 4.3 mWsec/cm², all values referring to the wavelength of highest efficiency, i. e., 296.7 mμ. The Council on Physical Medicine, U. S. A., has tentatively accepted as the average minimum erythema dose an intensity of 20 μW/cm² of radiation of wavelength 296.7 mμ, acting for 15 minutes, i. e., 18 mWsec/cm² total (see Blum, 1944). It is wellknown that the threshold dose varies considerably between different skin areas and different individuals, and there is also a pronounced seasonal variation of the skin's sensitivity (see p. 24). Blum and Terus (1946 b) have recently shown that the threshold dose also depends on the spectral character of the radiation in spite of its weighting by the same erythema action spectrum (that of Coblentz and Stair, 1934), being about 5 mWsec/cm² of UVE for short-wave ultraviolet from the low-pressure mercury arc (predominantly the wavelength 253.7 mμ) but rising to 18.5—52.5 mWsec/cm² for ultraviolet radiation of wavelengths mainly above 280 mμ, as from the carbon arc and sunlamps. It is evident that any average data on both the action spectrum and the threshold dosage of the photoerythema are provided with a high degree of unreliability when applied in practice; a main source of disagreement between different investigations may be the time elapsing before the observation of the response.

An important point to be mentioned here is that the reciprocity law is shown to be valid for the erythemal response of the skin within wide limits — at least several hours — of the duration of the exposure (Luckiesh, 1946; see also Meyer and Seitz, 1942, p. 204).

The threshold dosage applied as basis for the design of the UV-illumination system in the present investigation was *20 mWsec/cm² of UVE* (see Table 1). With respect to the character of "sun-lamp" of the ultraviolet sources to be used for the purpose this value may be considered reasonable.

The installation of the experimental UV-illumination system was to be made in some classrooms of a Primary and Secondary school, where the stay of the children could rise to about 5 hours per day. If the UV-illumination was on during all the lessons of the day the threshold dosage would then be reached by an UVE intensity of about 1 μW/cm² on the face and hands of the children. This figure formed the basis for the design of the irradiation component of the illumination system with respect to the erythema effect of it.

The Photophthalmia.

The prevention of ophthalmia must obviously be a most important task for the design of the UV-illumination system. Unfortunately, the dosimetric data available on this harmful irradiation effect do not permit reliable estimations of either the action spectrum or the threshold dosage on man.

Fischer, Vermeulen, and Eymers (1936) first studied the spectral dependency of the "eye-injurious" effect of radiation on rabbits, using the cornea-reflectoscope as detector of the injury. The threshold doses obtained were found to decrease considerably for wavelengths below about 300 mμ (see fig. 5), being 60 mWsec/cm² at 300 mμ but only 4 mWsec/cm² at 250 mμ. It seems questionable if an interpolation between the few data given in this spectral range is justified. In a recent study Cogan and Kinsey (1946) found an action spectrum of the photo-keratitis of quite a different shape, showing a pronounced peak of sensitivity for the cornea around 288 mμ with decreasing sensitivity towards shorter wavelengths. The investigation was made on rabbits and the criterion of keratitis applied was the ophthalmoscopic inspection of the cellular swelling (granulation) in the cornea. The threshold doses found by them for different wavelengths are shown in fig. 5 also. It is seen that the two investigations agree well in the region 285 -300 mμ but are widely deviating at shorter wavelengths. This may be explained by the different criteria used for the threshold response. The figure also shows, that the erythema threshold is reached before the ophthalmia threshold if the short-wave limit of the radiation is situated at 290—295 mμ, as in natural sunlight.

The potential ophthalmia-producing effect of short-wave ultraviolet radiation is of special interest in connection with the increasing use of low-pressure mercury lamps for air-disinfecting purposes. Up to 95 per cent of the radiation emitted by these sources consists of the wavelength 253.7 mμ (see Buttolph, 1942) and thus possesses a high potentiality for eye-danger. In spite of this, comparatively little work has been done in order to establish a threshold safety dosage. Rooks (1945) found in a self-investigation that an exposure of 3 mWsec/cm², as measured with a Rentschler photometer, was sufficient to cause a slight ophthalmia occurring 12 hours after the exposure to such a lamp equipment. This single datum obviously

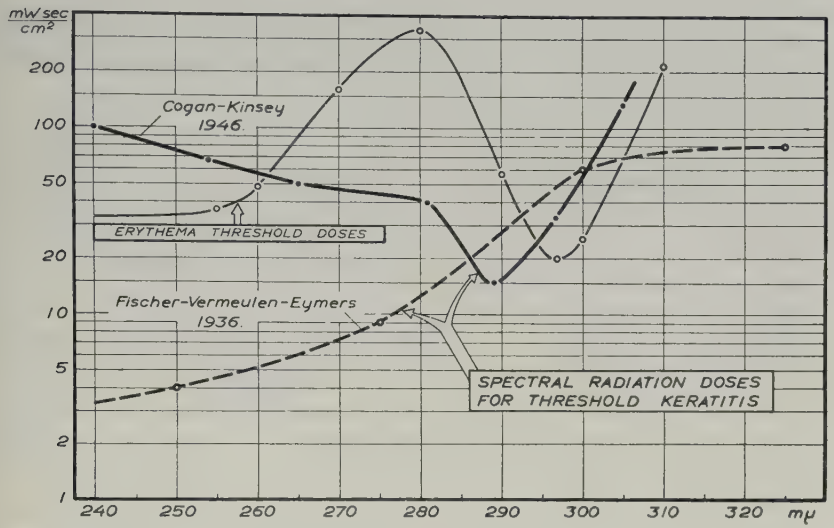

Fig. 5 Data on the threshold energy doses at different ultraviolet wavelengths for producing photoerythema and photophthalmia.

agrees better with the corresponding value found by FISCHER, VERMEULEN, and EYMERS than that by COGAN and KINSEY. *The only criterion on photophthalmia justified from the practical point of view is apparently the subjective pain and irritation*, whether this is accompanied by objective symptoms or not. It may be possible that short-wave ultraviolet rays, which are absorbed superficially in the cornea, may cause an irritation of the nerve endings there without observable granulation.

The interpretation of the action spectrum of FISCHER, VERMEULEN, and EYMERS led the International Commission on Illumination (1939) to stipulate that the intensity of radiation of wavelengths less than 280 mμ emitted by ultraviolet generators for general use may not exceed 1/10th of the energy radiated in the wavelength region 280—315 mμ. The Council on Physical Medicine, U. S. A., has recently (1943) stated that the intensity on the occupants of radiation of the wavelength 253.7 mμ, used for air-disinfecting purposes, may not exceed 0.5 μW/cm² during seven hours daily exposure, or 0.1 μW/cm² during constant exposure. These recommendations have been proved valuable for the safety of radiant air-disinfection installations (COBLENTZ, 1945 a). The corresponding dosage for a seven hours exposure is 12.5 mWsec/cm². It should be noted that

these data are valid for the horizontal plane in the region of the occupants and that only a small fraction of this radiation actually reaches the eyes of the occupants.

In the computations of the UV-illumination system both of these action spectra have been used. Radiant energy weighted by the action spectrum of COGAN and KINSEY is termed UVK and that weighted by the action spectrum of FISCHER, VERMEULEN, and EYMERS is termed UVX. The relative action factors applied for the mercury line spectrum are seen from Table 1. The reference wavelength is for UVK 288 mμ, and for UVX 254 mμ, with the corresponding threshold dosages — according to the respective authors — 15 mWsec/cm² for UVK and 4 mWsec/cm² for UVX. The value given by COGAN and KINSEY for the wavelength 288 mμ is, as seen in fig. 5, 20 mWsec/cm²; this is valid for rabbit eyes but they state that the human eye has only about two thirds of that resistance. The corresponding intensities for a threshold response on 5 hours exposure is 0.8 μW/cm² for UVK and 0.2 μW/cm² for UVX.

The eye irritation symptoms sometimes occurring in persons employed in localities with fluorescent lighting were ascribed by HARMON (1944) to the ultraviolet radiation emitted from these lamps. It is, however, definitely shown that the intensities of ultraviolet radiation both above and below 315 mμ in fluorescent light are very weak and, for instance, far smaller than in northern blue skylight (LUCKIESH and TAYLOR, 1945). Such disabilities may in most cases be due to the glare from unshielded lamps.

The Photo-Synthesis of Vitamin D.

The photo-synthesis of vitamin D is regarded as the most important ultraviolet irradiation effect on man and is responsible for the antirachitic action, both therapeutic and preventive, of sunlight. The provitamin predominant in human skin is 7-dehydrocholesterol, which after irradiation yields vitamin D_3. The content of the provitamin is many times higher in the skin than in other organs of the body. It occurs in the lowermost cells of the horny layer and in the prickle cells of the malphigian layer and is also present in excretory products washable from the skin. The absorption of vitamin D through the skin has been actually proved (cf. Chap. 2).

It should be pointed out that the vitamin D is only an *intermediate stage* in the chain of reactions induced by the action of ultraviolet on the provitamins, the end products being antirachitically inactive

suprasterols. Over-irradiation may also yield toxic products (toxisterol, substance 248) with hypercalcaemic effects in the body. In the main, the peak of the absorption spectrum of every new substance formed in the chain of photochemical transformations is moved towards shorter wavelengths. Thus, the maximum absorption of the provitamin is found at 282 mμ, of the vitamin at 265 mμ, and of the toxisterol at 248 mμ. As the action spectrum of every transformation process may be expected to coincide with the absorption spectrum of the substance undergoing the transformation, irradiation with short-wave ultraviolet is more likely to provide over-irradiation of the vitamin than is irradiation with longer wavelengths (above 280 mμ, cf. van Wijk, 1938).

The investigations of special interest for the present purpose are those dealing with *the action spectrum and threshold dosage* of the antirachitic effect *in vivo*, i. e., by irradiating the skin of rachitic infants or animals. Hess and Unger (1921) showed that sunlight filtered through ordinary window glass was deprived of its antirachitic ability for infants. Sonne and Reckling (1927) found the antirachitic effect on experimental animals to be limited to the spectral range 313—239 mμ, with the highest efficiency between 302 and 253 mμ. Hess and Anderson (1927) found an antirachitic effect on rats, for both the range 290—313 mμ (present in solar radiation) and the range 250—280 mμ, the efficiency being higher in the latter range. In recent studies Bunker and Harris (1937) and Knudson and Benford (1938) found by using large monochromators the action spectra of the threshold antirachitic effect shown in fig. 4. The data were obtained by irradiating a small area of depilated skin of rachitic rats. The relative action factors for the different wavelengths, obtained in these two investigations, are also given in Table 1. In general the curves agree well, but the maximum efficiency is found by Bunker and Harris at the wavelengths 297 mμ (cf. Bunker, Harris, and Mosher, 1940) while Knudson and Benford found it at 280 mμ. The latter curve coincides closely with the absorption spectrum of ergosterol and 7-dehydrocholesterol.

An interesting point is given by Knudson and Benford, namely, that *the increase of antirachitic effect on over-exposure* differs considerably between different wavelengths. For the wavelengths 303 and 297 mμ the increase of antirachitic effect was approximately proportional to the logarithmic increase of the dosage, but for shorter

wavelengths no increase was noted, and for the wavelength 265 mμ there was an actual decrease of the antirachitic effect by exposure above the threshold dosage (= first degree of healing). The explanation is assumed to be the destructive effect of the shorter wavelengths on the vitamin (cf. above). This discovery is of interest to combine with an observation made by Gorter and Soer (1930) by irradiating rachitic infants. The therapeutic dosage of quartz mercury arc irradiation was found to be smaller than the erythema threshold dosage only when the radiation below 280 mμ was filtered away from the radiation, and the effect of the unfiltered radiation was in all cases uncertain (cf. Gorter, 1934). It seems indicated, therefore, that *the highest yield of vitamin D by irradiation of the skin is reached in the spectral range 280—313 mμ*, as present in sunlight, while the shorter wavelengths may exert a destructive action overlapping the formation. A consequence of this is obviously that short-wave ultraviolet radiation, below 280 or 290 mμ, ought to be depressed in the ultraviolet component of the UV-illumination system.

If the relative action factor of the wavelength 297 mμ is taken as unity for both the action spectrum found by Bunker and Harris and by Knudson and Benford the relative course of the curves coincides almost perfectly with the curve of the erythema action spectrum for wavelengths above 290 mμ (see fig. 4, and Table 7, p. 96). For all ultraviolet sources of the type "sun-lamp", i. e., with the radiation below 290 or 280 mμ eliminated, the *erythemally-weighted radiation (UVE) may then be used as a simultaneous measure of the total antirachitic efficiency of the radiation.* A further assumption is of course that no weight is given to wavelengths longer than 315 mμ. In the case of medium-pressure mercury-vapour sunlamps such a combination of the erythema and antirachitic units is particularly justified, as there is practically no erythema-active radiation above 313 mμ in these lamps.

Regarding the *dosage of ultraviolet energy necessary for preventing and curing rickets* in infants the following data from the literature may be reported. Hess and Unger (1921) showed that irradiation with sunlight of only one wrist of a rachitic patient was sufficient to produce a general healing of the rickets. Gorter and Soer (1930, see Gorter, 1934) found that a daily dosage of 420 mWsec (0.1 Cal.) of a wavelength band around 297 mμ, applied on 200 cm^2 skin area, was sufficient to cure even florid rickets. No erythema developed,

which is to be expected when considering the dosage per unit area as only 2.1 mWsec/cm². That sub-erythemal dosages may cure rickets was also clearly demonstrated by Gerstenberger and Horesh (1931), who irradiated, for 12 hours daily, practically fully clothed rachitic infants with high intensities (about 700 lux) of light from tungsten-filament lamps enclosed in bulbs of Corex D glass (Mazda CX lamps). The dosage of erythemally-weighted radiation which proved to be antirachitic was in this case about 2.4 mWsec/cm² per day (cf. Luckiesh, 1946), and the skin area exposed was only that of the face and hands of the children. The figure apparently agrees well with that found by Gorter and Soer. It may thus be considered as proved that *a dosage of only about one tenth of the erythema threshold dosage applied daily on the face and hands is sufficient to secure the necessary supply of vitamin D to the infant's body.*

The yield of vitamin D per unit area of skin may be computed from the rat experiments previously cited to be about one I. U. per cm² per human erythema threshold dosage (see Table 1). It seems probable that the yield is considerably greater for the human skin.

If the UV-illumination for the classrooms is designed to produce a full erythema threshold exposure on the children during their daily stay in the school, this must obviously be expected to give an essential contribution to their vitamin D supply.

Bactericidal Effect of the Ultraviolet Radiation.

Regarding, at least, the bactericidal effect of the ultraviolet radiation no special design was devoted to it from the beginning. The action spectrum of this effect has a pronounced peak in the vicinity of 265 mμ (see, e. g., Hollaender, 1942), i. e., in a spectral range not suitable for direct irradiation of the occupants. Toward longer wavelengths the efficiency is steadily decreasing, as shown in Table 1. Some effect may, however, be expected also for a UV-illumination with the ultraviolet radiation completely restricted to the wavelength region above 280 or 290 mμ. The upper limit of the intensity is obviously governed by the direct responses of the occupants to the irradiation. As, however, the technical arrangement finally employed for the UV-illumination involved some emission of wavelengths below 280 mμ, the bactericidal effect became considerable. This will be discussed more completely in Chap. 12.

The Dosimetric Design of the Illumination.

In the application of the continuous ultraviolet irradiation by means of the artificial illumination system the exposure is limited by the threshold dosage of photoerythema and photophthalmia. By the units applied here these dosages are for the erythema about 20 mWsec/cm² (= 333 μWmin/cm²) of UVE and for the photophthalmia 15 mWsec/cm² of UVK or 4 mWsec/cm² of UVX, according to the data employed. From the interpretation given to the spectral dosimetric relations between photo-erythema and photophthalmia it is indicated that an erythema threshold exposure may be given on the face without the simultaneous production of photophthalmia if the short-wave limit of the ultraviolet radiation is situated at about 290 mμ. Calculating with a maximum time for the exposure of about 5 hours daily the erythema threshold would then be reached by an UVE-intensity of about 1 μW/cm² on the skin of the occupants. The ophthalmia power of the lamp to be used must be small in comparison with the erythema power. *Such an exposure given by mercury arc quartz lamps provided with a suitable filter for the limitation of short-wave ultraviolet radiation would imply a high antirachitic power, and besides the direct effects on the occupants some germicidal effect would also occur on the air and furniture of the room.*

It should be pointed out that this intensity of ultraviolet on the horizontal plane in the region of the occupants may be expected to give a considerably smaller intensity actually falling on the face of the occupants owing to the oblique incidence of the rays from the ceiling equipments. Especially the eyes are effectively screened from overhead radiation in usual employment.

By using the units for the biological power of ultraviolet sources previously proposed, i. e., the quotient of total weighted flux from the source and the corresponding threshold dosage, an estimate of the lamp power required to produce a threshold exposure in a given time is simply obtained by the formula

$$\frac{P \cdot t}{A} K = 1$$

in which

P = the power-value required,
t = the time of the exposure,

A = the area to be irradiated (i. e., the floor area of the room), and
K = the room utilization coefficient,

while 1 stands for *one threshold exposure*. This latter term may of course be chosen to the degree of exposure desired; for securing a sufficient antirachitic exposure it may be replaced by 0.1 if P stands for the UVE-power of a mercury lamp with short-wave absorbing filter.

Applied to the actual case of providing a threshold erythemal exposure on school children during their stay in the classroom, with the approximate floor area 50 m^2 (500 000 cm^2), and with an exposure time of 3—5 hours daily ($\approx$ 15 000 sec.), and assuming the utilization coefficient to be comparatively low (about 0,20), the total erythema power required will be

$$P = \frac{500\,000}{0.20 \cdot 15{,}000} = 167.$$

Shared between four equipments each ultraviolet source should have an erythema power of about 42 cm^2/sec. Considering the maintenance factor of the installation, which allows for the depletion of the ultraviolet output from the sources during the first period of use, and the smaller intensity on the face of the occupants, even a higher value would *a priori* seem applicable. On this basic assumption the experiments on the technical arrangement of the UV-illumination system were started.

CHAPTER 5.

The Technical Arrangement of the UV-Illumination System.

The technical features of the illumination system developed in the present investigation, with the simultaneous emission and distribution of ultraviolet radiation (UV) and visible light, include three special essential components:

UV-emitting source,
UV-scattering reflector, and
UV-reflecting paint on ceilings and walls.

Each of these components of the UV-illumination system has been a subject for special investigations and will be treated separately below. The methods employed for the physical measurements carried out are described in Chap. 7.

The UV-Source[1].

Among modern radiation sources now available, the *mercury vapour lamp* is best suited for the purpose of providing the basic source of the UV-illumination system. The mercury arc quartz lamp, operating at a vapour pressure of about one atmosphere, emits considerable amounts of energy in the short- and medium-wave ultraviolet range (see, e. g., RÖSSLER, 1940; ORANJE, 1943; FORSYTHE and ADAMS, 1944; COBLENTZ, 1945). With a suitable glass filter around the quartz burner more or less of the radiation below the wavelength 290 mμ can be absorbed (see, e. g., KREFFT, 1942 a). Such lamps are commonly called "*sun-lamps*" and with certain specifications are accepted for general use by the Council on Physical Medicine, U. S. A. (1934, 1940). A disadvantage of the medium-pressure lamp from the biological point of view is, however, the relatively small radiation output in the long-wave ultraviolet spectrum.

It is a well-known fact that mercury vapour lamps combined with incandescent lamps in special proportions give a "daylight illumination", widely used for industrial lighting (see, e. g., MATTHEWS, 1940; ORANJE, 1943; cf. p. 18). For the illumination purpose also the mercury lamp could then be expected to provide a suitable source.

The UV-source finally selected for the UV-illumination system was such a medium-pressure mercury lamp, made by the Swedish lamp factory LUMA under the trade name LK 120. The lamp, adapted for the present purpose, is shown in fig. 6. The small inner tube is made of quartz, with electrodes of a tungsten alloy. It is surrounded by a thin bulb of a molybdenum-containing glass, which strongly absorbs wavelengths shorter than about 290 mμ. The energy input, with the choke coil, is 120 watts.

The *spectral energy output* in the ultraviolet range has been deter-

[1] The sources employed were made available by LUMALAMPAN AB, Stockholm.

Fig. 6. The UV-source (LK 120). The small, inner mercury-arc quartz tube (the burner) is surrounded by an outer bulb (the filter) of short-wave ultraviolet-absorbing glass.

mined in several ways, as will be described later (Chap. 7). All the quantitative measurements, in absolute values, are based on comparisons with a mercury arc standard lamp ("UV-Normal"), designed by KREFFT, RÖSSLER, and RÜTTENAUER. The values given below of the total ultraviolet flux emitted per wavelength are computed with allowance for the intensity distribution curve of the ultraviolet radiation from the lamp.

In figs 7 and 8 the spectral energy distribution for the range below 350 mμ obtained by spectroradiometric comparison with the UV-Normal lamp is given for a new LK 120 lamp and for an LK 120 lamp after 400 hours of use. Fig. 19 (p. 88) gives a survey of the relative spectral energy distribution below 450 mμ, obtained by the method of direct semi-quantitative spectrography described on p. 85. Finally, Table 2 contains the values for the estimation of the erythema power (UVE), the photophthalmia power (UVK and UVX, according to the different action spectra employed) and the germicidal power (UVG) of the LK 120 lamp radiation, according to the description given in the previous chapter. Table 3 gives, for comparison, the same calculations made on the radiation data for the 250 watt

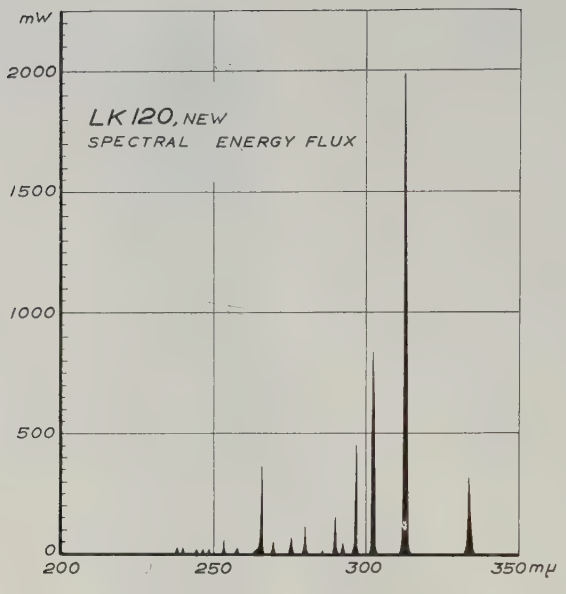

Fig. 7. Spectral energy flux in ultraviolet emitted by a new LK 120 lamp.

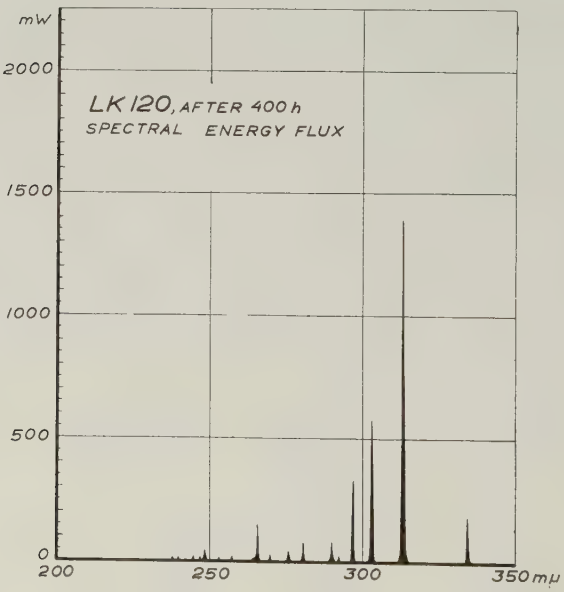

Fig. 8. Spectral energy flux of an LK 120 lamp after 400 hours of use.

Table 2. *Absolute and Weighted Radiation Data of the LK 120 Lamp.*

Wavelength, mμ	Intensity at 1 meter μW/cm²	Absol. Flux mW	UVE mW	UVK mW	UVX mW	UVG mW
365	—	3,900	—	—	—	—
334	2.93	288	—	—	—	—
313	20.18	1,980	59	40	40	20
303	8.43	826	454	107	41	41
297	4.61	452	452	212	45	122
293	0.42	41	29	31	7	16
289	1.62	159	40	159	35	73
280	1.21	119	7	44	43	83
275	0.65	64	4	22	29	51
270	0.37	36	5	12	20	33
265	3.70	363	91	109	240	363
257	0.18	17	8	5	14	14
254	1.14	112	61	28	99	75
248	0.60	59	34	13	59	30
< 248	0.45	44	25	9	50	25
Total below 315 mμ....	43.56	4,270	1,270	790	720	946
Total below 285 mμ....	8.30	814	235	242	554	674
Weighted Power, cm²/sec	—	—	70	79	180	3,150 (19 m²/min)
Efficiency, cm²/sec.watt	—	—	0.6	0.7	1.5	26

UV-Normal lamp, with the data according to Rössler (1939). The upper spectrogram of fig. 20 (p. 89) shows the spectral energy distribution of this lamp found by the semi-quantitative spectrographic method. This lamp may be taken as a typical example of a common therapeutic quartz lamp.

The *absorption of short wavelengths by the outer bulb (filter)* in the LK 120 lamp is clearly seen from the tables. The emissions per watt of input energy for the spectral lines 334 and 366 mμ are about equal for both of the lamps, but for the total ultraviolet below 315 mμ the efficiency of the quartz lamp without the filter is 1.7 times higher than for the LK 120 lamp. The corresponding ratio for the UVE-efficiency is 1.6, for the UVK-efficiency 1.8, for the UVX-efficiency 3.4, and for the UVG-efficiency 2.7.

When the action spectrum of Cogan and Kinsey is used for the

Table 3. *Absolute and Weighted Radiation Data of the UV-Normal Lamp* (Primary data from RÖSSLER, 1939).

Wavelength, mμ	Intensity at 1 meter μW/cm²	Absol. Flux mW	UVE mW	UVK mW	UVX mW	UVG mW
365	69.68	7,530	—	—	—	—
334	5.09	550	—	—	—	—
313	46.73	5,050	150	100	100	50
303	19.90	2,150	1,180	280	110	110
297	10.64	1,150	1,150	540	120	310
293	1.02	110	80	80	20	40
289	4.07	440	110	440	100	200
280	7.13	770	50	280	280	540
275	2.68	290	20	100	130	230
270	3.15	340	50	110	190	310
265	16.19	1,750	440	530	1,160	1,750
257	1.02	110	50	30	90	90
254	15.08	1,040	570	260	930	700
248	8.05	870	500	190	870	440
< 248	8.75	940	570	200	1,000	500
Total below 315 mμ....	144.41	15,010	4,920	3,140	5,100	5,270
Total below 285 mμ....	62.05	6,110	2,250	1,700	4,650	4,560
Weighted Power, cm²/sec	—	—	246	314	1,275	17,500 (105 m²/min)
Efficiency, cm²/sec.watt	—	—	0.98	1.26	5.10	70

evaluation of the *ophthalmia-producing power* of the radiation (UVK), it appears that the filter does not markedly influence the ratio of erythema power to keratitis power. If, on the other hand, the action spectrum according to FISCHER, VERMEULEN, and EYMERS is employed (UVX), the eye-protecting effect of the filter is clearly indicated. Personal experience, acquired during the measurements of both types of lamps, is undoubtedly in favour of the filter diminishing the risk of eye-irritation from the same erythema-effective exposures. The same experience is also reported by VAN WIJK (1937), regarding the effect of a similar filter for the PHILIPS quartz lamp "Biosol".

The quotient UVB/UVC in the LK 120 lamp radiation is about 5, i. e., the energy emitted in the spectral range 280—320 mμ is 5 times

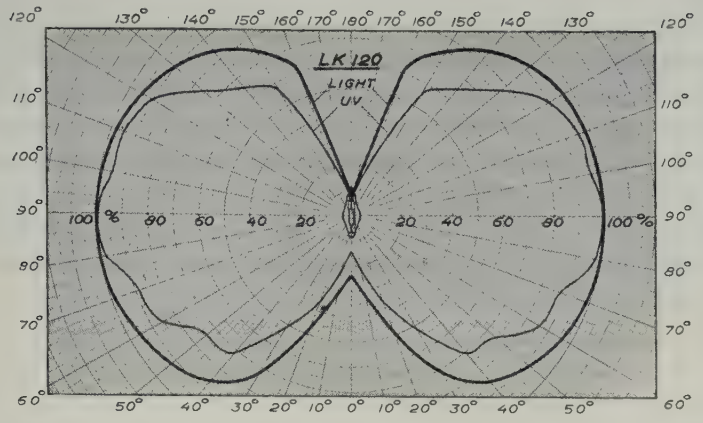

Fig. 9. Intensity distribution curves of light, and ultraviolet radiation of wavelengths below 315 mμ for the LK 120 lamp.

that below 280 mμ. This ratio is approximately unity for the UV-Normal lamp radiation. The International Congress on Illumination (1935) recommended that for eye-safety this ratio should not be less than 10 for ultraviolet-containing illumination systems (I. C. I., 1937). A consequence of the comparatively strong emission of short wavelengths by the UV-source employed is the gain in *bactericidal power* (UVG). As will be shown later, the air-disinfecting effect of the UV-illumination with the LK 120 lamp as UV-source is very marked, and the risk of eye-inflammation seems to be negligible; not a single case has been reported from the experimental installations.

The *erythema power* of the lamp has also been *physiologically tested* by means of a series of increasing exposures upon normal unpigmented skin of a number of different persons. The erythema threshold for the most sensitive subjects was reached after 5—10 minutes' exposure at a distance of 50 cms from the unshielded lamp. The value computed from the spectral data given, assuming the threshold to be 20 mWsec/cm², is 7 minutes. For most of the persons longer exposures were necessary.

Some isolated experiences regarding the ophthalmia-producing power of the lamp indicate that the ophthalmia threshold is reached shortly before the erythema threshold, when the face is directly exposed to the radiation.

The *intensity distribution curves* of visible light, and ultraviolet radiation below 315 mμ for the LK 120 lamp are seen from fig. 9.

The light intensities for the different angles were measured with a colour-corrected selenium photocell (Weston Photronic cell), and the ultraviolet intensities were obtained as the difference between quartz-transmitted and glass-transmitted radiation, indicated by a selenium photocell (see p. 91). Most of the radiation, especially ultraviolet, is obviously emitted in the horizontal direction. The short-wave absorbing filter is thinner in the middle part of the lamp because of an enlargement of the bulb, and this is also shown in the distribution curve of the ultraviolet radiation.

The total *luminous output* of the LK 120 lamp was determined in the usual way by means of an integrating Ulbricht sphere photometer and colour-corrected photocell, and the average value from several lamps was 4,000 lumens. The luminous efficiency is then about 32 lumens per watt, in agreement with ordinary mercury lamps for illumination purposes.

In order to get a proper *colour of the light* in the illumination, each LK 120 lamp had to be combined in the same fixture with three 150-watt incandescent lamps, each with a luminous output of about 2,100 lumens. The ratio of incandescent luminous flux to mercury arc luminous flux is then about 1.5 : 1, which is known to be a good value in practice (Matthews, 1940).

The *ratio of UVE-flux and luminous flux* of the LK 120 lamp alone is about 0.3 mW per lumen. At an illumination level of 1 lux (= 1 lumen/m^2) the intensity of UVE is therefore about 0.3 mW/m^2, or 0.03 μW/cm^2, and the UVE-intensity of 1—2 μW/cm^2 required for the UV-illumination corresponds to an illumination level of 60—70 lux of the mercury-light alone. In combination with incandescent light in the proportion 1.5 : 1 the same UVE-intensity is reached by about 160 lux of illumination, which is a very reasonable value for indoor artificial illumination. These considerations demonstrated the possibility of using the LK 120 lamp as the source for the UV-illumination. The actual UVE-intensity in a room provided with UV-illumination must, however, also be evaluated with respect to the different coefficients of utilization for visible and ultraviolet radiation (see p. 76), and the estimate above is only indicative.

The radiation output of the lamp, both visible and ultraviolet, is continuously *decreasing during the time of use* (cf. Seitz, 1939). After 400 hours, the ultraviolet output is only about one half of the initial value, as seen from fig. 8. The decrease of the luminous output is

shown by measurements to be somewhat smaller. The main reason for this uneconomical state is an obvious deposit of black vaporised electrode substance upon the inner wall of the quartz tube, but devitrification of the quartz may play some role too. The spectral transmission of the outer glass filter seems, however, not to change to any great extent, at least not during the first 400 hours of use.

Unfortunately, allowance could not be made for this deterioration to the extent desired, as the possibilities of obtaining these lamps were very restricted during the war years when the investigations were carried out.

The UV-Reflector[1].

The fitting of the UV-illumination system must distribute both the visible and the ultraviolet radiation, without the internal losses being too great, in order to produce a reasonably uniform illumination and irradiation over the horizontal working plane of the room. Glare from the sources must also be avoided.

Ordinary glass of some millimeters thickness, as used in most luminaires for artificial lighting, completely absorbs ultraviolet radiation of wavelengths shorter than about 315 mμ (see, e. g., Koch and Widmark, 1928). The ultraviolet-transmitting glasses now available are still too expensive for general use in luminaires.

Hence the fixture finally adopted for the UV-illumination system was of the *reflector type*, consisting of vertical concentric rings of aluminium, open upwards and downwards, as shown in the photograph of fig. 10. The inside surfaces of the rings were chemically etched in order to give a diffuse reflection throughout the visible and ultraviolet spectrum (see Taylor and Edwards, 1931). The reflection factor of the treated surface for the wavelength 297 mμ was spectroradiometrically determined to be 70 per cent, which is in agreement with the data given by Taylor and Edwards for this kind of surface treatment. The outer surfaces of the rings were painted with a *special ultraviolet-reflecting paint*, described below. In the bottom of the lowest ring of the reflector a diffusing opal glass plate could

[1] The design of the reflector was made in collaboration with G. Hassel, Swedish Lighting Development Society, Stockholm. The reflectors were manufactured by Asea Electric Ltd., Stockholm.

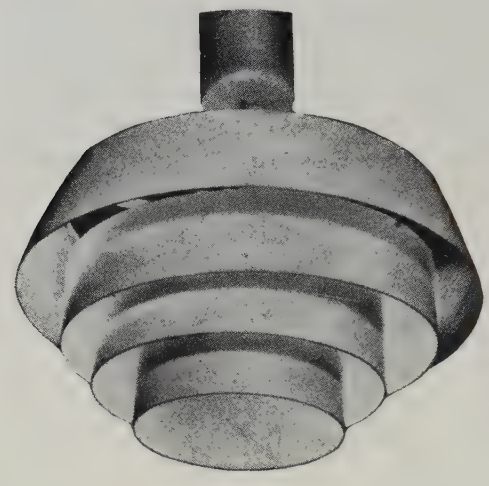

Fig. 10. The UV-reflector. The concentric rings are made of aluminium. The inside surfaces are chemically etched and the outside surfaces are painted with an ultraviolet-reflecting paint. One LK 120 lamp and three 150-watt incandescent lamps are placed in the reflector.

be placed, in order to diminish the ultraviolet emission from the equipment.

The mercury lamp LK 120 was placed in the centre of the reflector, surrounded by the three incandescent lamps. The heights and relative positions of the rings were so arranged that the bright mercury lamp could be seen only from a point just below the fixture and so that the glare from the other lamps was also reasonably avoided. With the opal glass plate situated in the lowest ring the mercury lamp was completely invisible from below. The choke coil of the mercury lamp was placed in a ceiling box.

The *intensity distribution curves* of visible light, and ultraviolet radiation of wavelengths below 315 mμ from the reflector, with and without the opal glass plate, are shown in fig. 11. The visible radiation is distributed upwards and downwards to approximately the same extent, while the ultraviolet distribution is predominantly indirect, especially when the opal glass plate is in position. The horizontal component of the distribution curve is obviously almost completely absent for both the visible and the ultraviolet radiation.

The *efficiency of the reflector* with respect to the *luminous output* was found to be 57 per cent, and with respect to the light from the central mercury lamp only it was 54 per cent. These luminous efficiency determinations were made in the usual way with the aid of a large Ulbricht sphere photometer. This method was not applicable

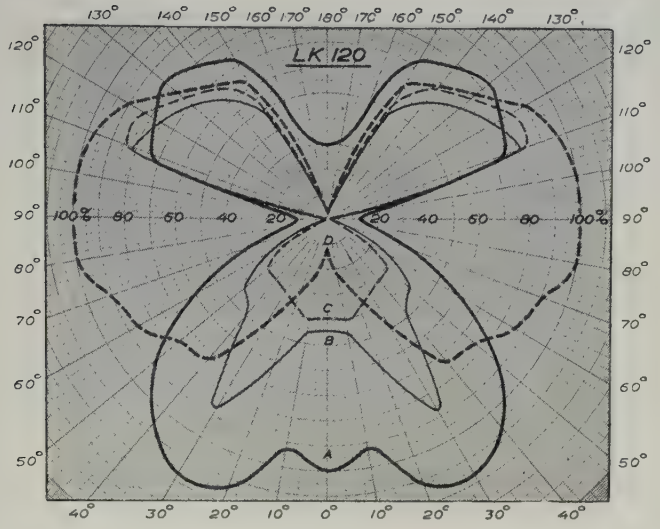

Fig. 11. Intensity distribution curves of the UV-reflector. A = light distribution, B = ultraviolet distribution from the reflector without opal glass plate, C = ultraviolet distribution with opal glass plate, D = ultraviolet distribution from the bare LK 120 lamp.

for determinations of the total ultraviolet efficiency of the reflector, as the paint on the inside of the sphere was found to absorb the ultraviolet radiation. The *ultraviolet efficiency* of the reflector was then computed from the intensity distribution curve of the ultraviolet radiation (see p. 84). This computation was made in such a manner that the component efficiencies of the direct and indirect radiation were also obtained. The values are given in Table 4. It is seen that the opal glass plate in the bottom of the reflector diminishes the efficiency of the direct ultraviolet component by one half. The component efficiencies are later used for the calculation of room utilization factors.

Table 4. *Efficiency of the Reflector for Ultraviolet below 315 mμ.*

Reflector	Direct component	Indirect component	Total[1]
Without opal glass....	0.20	0.28	0.48
With opal glass	0.10	0.32	0.42

[1] The horizontal component is neglected.

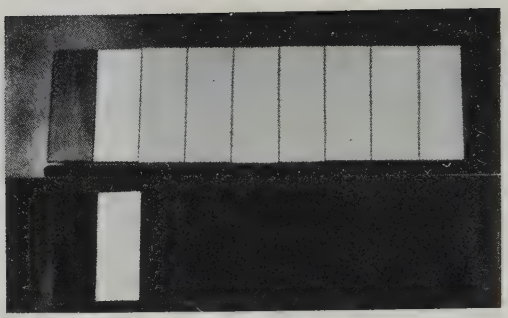

Fig. 12. Ultraviolet reflection photographs of various paints; the upper series for ordinary light, the lower series for ultraviolet radiation. From the left: unpainted wooden plate; barium sulphate in casein (the UVR-paint); barium sulphate in oil; the rest, zinc oxide and titanium oxide in oils.

As the ultraviolet reflection factors of the ring surfaces, especially the external painted surfaces, decrease towards shorter wavelengths, the efficiency values given must be considered as averages. For wavelengths below 290 mμ they are probably somewhat smaller.

The UV-Reflecting Paints.[1]

Most common paints for indoor use, such as oil paints and those containing zinc oxide or titanium oxide as pigment, have a negligible or very small reflecting power in the ultraviolet spectral range (see Luckiesh and Holladay, 1931 a; A. H. Taylor, 1934 b). This may be clearly illustrated by *ultraviolet photography* (fig. 12). Some common mixtures were painted on wooden plates and photographed, both in the usual way, with a yellow filter and panchromatic film (the upper series), and also with a special "UV-camera", equipped with UV-filter and quartz lenses (the lower series). The UV-filter used was a silvered quartz plate with transmission only in the range 310—330 mμ, combined with the Schott filter UG 5 (see also p. 90.)

To install a UV-illumination system in a room with no reflection of the ultraviolet rays by the ceiling and walls would obviously be as ineffective and uneconomical as to install a common lighting system in a room with black or very dark ceiling and walls.

[1] The preliminary experiments were carried out in cooperation with T. Johansson, Military Research Institute, Department I, Stockholm. The definite composition was made in cooperation with Ferniss AB Ferbo, Stockholm, who also manufactured the paints.

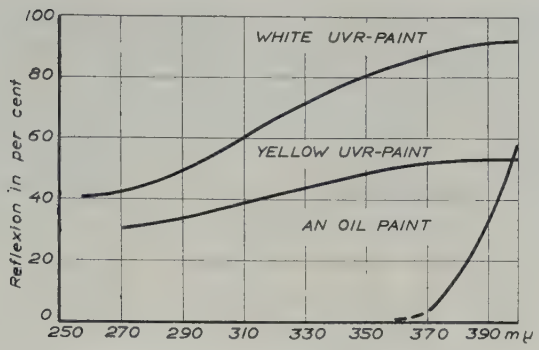

Fig. 13. Spectral reflection in ultraviolet of the UVR-paints compared with an ordinary oil paint.

The investigation of the factors determining the UV-reflecting ability of a paint leads to the conclusion that the *paint pigment* must have good UV-reflecting power, and the *paint binder* good UV-transmitting power. Different paints with improved UV-reflecting power were described by Luckiesh and Holladay (1931), and other such paints were recently studied by Willcock and Soller (1940). As binder for the paint, casein or nitrocellulose lacquer has mostly been used, and the pigment has in most cases been magnesium carbonate. A survey of this field was recently given by Déribéré (1947), who also points out the possibility of using wall-papers for ultraviolet-reflecting purposes.

The experiments carried out during this investigation resulted in the discovery that a good UV-reflecting paint could be obtained by using *barium sulphate as pigment and a casein solution as binder.* With these intentions the Swedish paint factory Ferniss AB Ferbo has made two useful UV-reflecting paints ("UVR-paints"), one white and the other with a slightly yellow tint. The spectral reflection measurements of these paints have been made spectroradiometrically, using magnesium oxide as a standard (see p. 90), with the results shown in fig. 13.

During filter measurements made with the UV-Normal mercury lamp placed in a special Ulbricht sphere (p. 81), which had the inside surface freshly painted with the white UVR-paint, it was noted that the reflection factor in the spectral range 280—320 mμ decreased exponentially to about 80 per cent of the initial value during the first hours of the strong irradiation. This is probably due to a photoche-

mical influence upon the casein binder. The same observation was also made by Willcock and Soller on some similar paints.

A disadvantage of these two UVR-paints is that they are not quite resistant to water, and therefore not washable. For use in the UV-reflectors it was considered necessary to have a washable paint. The laboratory of the Ferbo paint factory was also successful in making such a paint with approved ultraviolet reflection for this purpose. The reflection factor in the range around 300 mμ was, however, not higher than about 30 per cent. This is the main reason why the efficiency of the reflector for ultraviolet was lower than for visible light.

CHAPTER 6.

The Radiation Climate of the Experimental Rooms.

The Experimental Rooms Selected.

For the purpose of studying the hygienic and physiological effects of the UV-illumination two ordinary class rooms of a large Secondary school in Uppsala, and the single room of a small Primary school situated in the outskirts of the town, were equipped with the UV-illumination system. In each of the Secondary school rooms, both with a floor area of 55 m^2 and a ceiling height of 3.55 m, the walls and ceilings were painted with the white UVR-paint, and four of the UV-equipments were installed at a height of 2.7 m (see fig. 14). The Primary school room was somewhat smaller, with a floor area of 45 m^2 and a ceiling height of only 2.7 m. The ceiling was painted with the white UVR-paint, the walls with the yellow UVR-paint. Here also four UV-equipments were installed, 2.1 m above the floor.

Theoretical Estimation of the Radiation Intensities.

From the dimensional data of the room, the radiation data of the sources and the efficiency data of the equipments given above, the intensities of ultraviolet energy upon the working planes of the rooms were calculated in the same way as is recommended for accurate de-

Fig. 14. One of the experimental classrooms in the Secondary school, equipped with UV-illumination.

signs of interior illumination, i. e., by means of the '*three-curves*' *method* of HARRISON and ANDERSON, as recently described by BOAST (1942). The accuracy of this method is said to be better than 10 per cent.

The principle of the method is that the radiation from the equipments is divided into three components, a direct one (D), a horizontal (H), and an indirect (I), which are treated separately and finally added. For each component the *coefficient of distribution* (C), giving the ratio of the flux received at the working plane to that emitted by the equipment, is obtained from average nomographic charts, with allowances for the room index as a measure of the shape of the room, and for the wall and ceiling reflection factors. The room index is also taken from a nomographic chart, and is determined by the ratio of the ceiling or mounting height to the room width, and the ratio of the room length to the room width. To get the *coefficient of utilization* (K), of the complete system, the distribution coefficients (C) are weighted against the respective efficiences (η) of the equipment, i. e.,

$$K = C_D \eta_D + C_H \eta_H + C_I \eta_I .$$

In the case of the ultraviolet radiation from the actual equipments, the horizontal radiation component ($C_H \eta_H$) is negligible.

Besides the coefficient of utilization, a *maintenance factor* (M) must also be introduced, allowing for the diminution of the radiation intensities with the ageing of the sources and also for the accumulation of dust and dirt on the equipments and the reflecting surfaces. Then, the density of the radiant flux (E) on the horizontal working plane, assumed to be 0.9 m above the floor, is computed from the general formula

$$E = \frac{n\,F\,K\,M}{A}$$

where A equals the room area and n the no. of sources, each with the radiation flux F.

For the installations in the two larger, Secondary school rooms, the coefficient of utilization (K) for the *ultraviolet radiation* was found to be 0.24, i. e., 24 per cent of the ultraviolet radiation emitted by the UV-sources is received on the working plane. With the ultraviolet absorbing opal glass plates placed in the reflectors, the value of K was diminished to 0.17. In the smaller, Primary school room the values were 0.25 and 0.18 respectively. The maintenance factor (M) was, by analogy, estimated to be 0.70, provided that the UV-sources were exchanged after about 400 hours of use. The initial intensities are of course obtained by putting M equal to unity.

The coefficient of utilization of the illumination system with respect to the *visible radiation*, i. e., the light, was found to be about 0.35 for all the rooms, with only a slight reduction when the opal glass plates were in the equipments.

Table 5 gives the intensities in the experimental school rooms of the different spectral radiation components of interest, obtained by this method of calculation. *It gives a synopsis of the radiation climate, to which the children were exposed during the investigation.* The approximate threshold time values given are strictly valid only for horizontally exposed surfaces. Actual measurements indicated that the intensities on vertical surfaces in the work region were about 30—50 per cent lower, with correspondingly higher values of the time for threshold exposures.

For the purpose of the medical investigation it was stated that *the illumination should be in use during at least three lessons daily* (*about 150 minutes*) and more if necessary. During the darkest winter months the artificial illumination was normally in use for all the lessons (about 300 minutes).

Table 5. *Intensities of Visible and Ultraviolet Radiation in the Experimental Classrooms.*

Component of Radiation	Secondary School Rooms		Primary School Room	
	Intensity at the horizontal working plane	Approx. time for threshold exposure	Intensity at the horizontal working plane	Approx. time for threshold exposure
Light	270—300 lux	—	400—500 lux	—
UV 400—315 mμ	5 μW/cm²	—	6.7 μW/cm²	—
UV below 315 mμ	5.1 »	—	7.0 »	—
UV below 285 mμ	1 »	—	1.3 »	—
UVE	1.5 »	220 min.	2.0 »	160 min.
UVK	0.9 »	190 »	1.2 »	145 »
UVX	0.8 »	85 »	1.1 »	65 »
UVG	1.1 »	20 »[1]	1.3 »	17 »[1]

Opal glass screens in equipments: 30 per cent lower intensities.
Initial conditions: 40 per cent higher intensities.

[1] For about 99 per cent killing of *E. coli* (40 % rel. humidity). See Chap. 12.

If the intensity of the visible radiant energy in the experimental rooms (300 lux) is transformed to the equivalent absolute intensity of the reference wavelength in the luminosity curve (555 mμ), by means of the mechanical equivalent of light (= 1.5 mW per lumen), the value 45 μW/cm² is obtained. The intensities of weighted erythema radiation (1.5 μW of UVE) in the experimental rooms are then biologically comparable with about 10 lux of illumination. This gives an idea of the intensity relation of effective visible, and effective erythema-producing radiation.

Experimental Controls of the Radiation Intensities.

The intensity values computed have been checked in physical as well as physiological ways. With a *photoelectric filter-difference device* (see p. 91) indicating only the radiation below 315 mμ, a reading was taken of the intensity one meter away from the bare UV-source (LK 120), and then at twenty places in one of the Secondary school rooms, with the illumination on. By assuming the intensity of radiation below 315 mμ at one meter from the LK 120 to be 44 μW/cm², as determined by other measurements (Table 2), the intensities in the school room measured in this way were found to vary from 3.2 to 9.4 μW/cm², with an average of 6.3 μW/cm². The correspond-

ing intensity calculated for a new installation was 7.3 μW/cm² (Table 5), with respect to the maintenance factor 5.1 μW/cm². No attempt has been made to correct these readings for the influence of the small change in spectral composition of the radiation due to the reflection from the ceiling and walls. The measurements were made with new LK 120 lamps, but after the installation had been in use for one year.

The *physiological test* employed has been the development of erythema. It was found that in the larger Secondary school rooms where the erythema threshold exposure should be reached after 220 minutes, the children did not show any skin irritation after the daily three hours of exposure. The teacher, who sometimes had to work there for longer times in the day, felt a slight hotness in the face after about five hours in the illuminated room. Similar experiences were also obtained by other subjects. In the Primary school room, with the higher intensities, *all the children had slight but definite yellowish-brown pigmentation of face and hands* after the first weeks of the experiment. The pigmentation of the children is obviously a sign of adaptation to the ultraviolet radiation.

At the beginning of the experiment the opal glass plates were used in the reflectors, as the calculated intensities, especially of the ophthalmia-effective radiation, seemed to be too high. The plates were taken away one by one during the first week, without any injurious effect. The intensities were then about 40 per cent higher than indicated in the table above. The Council on Physical Medicine, U. S. A. has stated (1943) that the intensity of short-wave bactericidal ultraviolet radiation in a room must not exceed 0.5 μW/cm² on the occupants when the exposure is 7 hours, and 0.1 μW/cm² when the exposure is 24 hours. These safety intensities are calculated on the basis of the erythema response (cf. p. 55).

Experiences from other similar installations of UV-illumination, with about the same intensities as in the school rooms (a textile factory, and personal laboratories at the Institute), indicate that even eight hours of exposure, and probably more, to the illumination do not cause more than a slight or moderate erythema, to which the skin is rapidly adapted, but *without any eye discomfort. No single case of this has hitherto been reported from the different installations made.*

The main reason why the intensity of the ophthalmia-effective radiation can be kept at such comparatively high values without immediate risk of eye irritation, is certainly that in ordinary employment

the eyes are very effectively screened from the overhead radiation. The reflection from the lower parts of a room for the short-wave ultraviolet radiation is in most cases negligible. It should be noted, however, that ordinary book and writing paper reflect 20—40 per cent of radiation around 300 mμ (see A. H. Taylor, 1934 b). In the case of a hospital room, with patients lying in beds, the risk of photophthalmia from such a UV-illumination would probably be considerably higher.

An important advantage of the prevalent short-wave ultraviolet radiation, despite the danger of latent eye-injury, is *the marked bactericidal effect of the illumination throughout the room.* The interpretation of this will be given in Chap. 12. An unfortunate effect, on the other hand, is the deleterious action on most flowers and plants in the room, which seems unavoidable.

The *illumination level* (300—500 lux) in the school rooms equipped with UV-illumination systems was considerably higher than is usual in Swedish classrooms. Some glare from the reflectors was inevitable, but in general the installations became highly valued by both teachers and children. The colour of the light was pleasant, being reminiscent of natural sunlight.

To sum up it may be said, that *the exposures of ultraviolet energy in the Secondary school rooms were just below the erythema threshold, and in the Primary school room just above this threshold.* No case of discomfort from the eyes or otherwise has been reported, in spite of the comparatively high intensity of short-wave, strongly bactericidal radiation present in the illumination.

CHAPTER 7.

The Physical Methods Employed.

The development of the UV-illumination system described in the last chapters has obviously required a number of special physical and technical measurements. The methods employed have generally been rather primitive, because of the lack of suitable instruments. For instance, the only photoelectric devices available have been selenium barrier-layer photocells, which also had to be used where the

special phototubes made for ultraviolet radiation would have been more suitable. The lack of a sensitive, calibrated thermoelectric device has made all the quantitative radiation measurements, in absolute units, dependent upon the constancy of a standard lamp for ultraviolet radiation.

Special attention should be drawn here to the *semi-quantitative spectrographic method* described on page 85, which has been developed during the present investigation.

Measurements of Spectral Energy Distribution.

The UV-Normal Lamp.

All the measurements of spectral intensities and spectral energy distributions have been based upon comparisons with the *UV-Normal lamp*, described by KREFFT, RÖSSLER, and RÜTTENAUER (1937), and previously made by OSRAM A. G., Berlin. This lamp is a medium-pressure mercury arc quartz lamp of 250 watts, D. C., and is said to give a constant spectral energy output, within the limits $\pm$ 5 per cent, during 200 hours of use, when burning under certain given conditions. Spectral data for the lamp, in absolute units, are given by FISCHER (1937), RÖSSLER (1939) and WEISSFLOG (1940). There are some differences between the results of these measurements, but for the range 315—250 mμ, which is of greatest interest in this investigation, the data given by the different authors are fairly uniform. The constancy of the lamp is supported by WEISSFLOG.

The lamp available for this investigation was received direct from OSRAM (Berlin), and has only been used for this work. The spectral data given by RÖSSLER have been used as standard values (Table 3, p. 66). It has not been possible to check these values further.

The lamp is run on direct current from a battery of about 200 volts, and is in the vertical position with the anode downwards. The arc is started by means of a Tesla inductor or other ionization device. After the starting period the input power of the lamp is adjusted to exactly 250 watts by means of a resistance. The arc voltage is then about 130 volts. A complete description of the use of the lamp is given by KREFFT (1942 b).

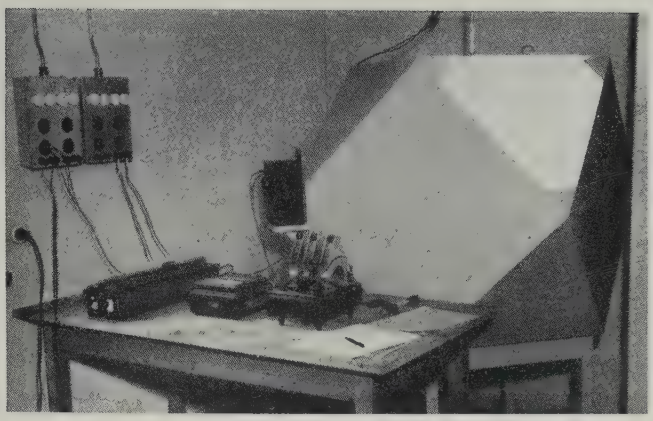

Fig. 15. The Ulbricht sphere photometer with filter and photocell equipment for measuring ultraviolet radiation.

The Filter Method[1].

To get a rough estimation of the energy output in the *spectral range 260—315 mμ* of different mercury lamps the following filter-method according to KREFFT and RÖSSLER (1936) was employed (see also KREFFT, 1942 b).

The lamp was placed in the centre of an integrating Ulbricht sphere photometer (in this case a tetradecahedron, fig. 15), the inside surface of which was painted with the white UVR paint. In a small opening, screened by an aluminium plate from the direct radiation of the lamp, a filter combination was placed with the spectral transmission seen in fig. 16, and behind the filter a large selenium barrier-layer photocell, connected to a sensitive low-resistance galvanometer. The reading of the galvanometer is then a measure of the energy output of the lamp in this wavelength range, proportional to the mean spherical radiation power. The reading was compared with the same reading of the UV-Normal, where the output in this range is known in absolute units. This method applied to the LK 120 lamp gave the preliminary value of 4.8 watts for the radiation between 260 and 320 mμ. Different LK 120 lamps showed very small variations.

The values obtained in this way are, however, only correct when the relative spectral energy distribution of the test lamps is identical with the UV-Normal. This is not the case with the LK 120 lamp, where the outer bulb decreases the intensities of the shorter wavelengths. If the relative intensity relations between the different wavelengths in the test lamp radiation are known, a correction

[1] The measuring equipment described below was provided by the Royal Institute of Technology, Department of Applied Electrical Engineering, Stockholm.

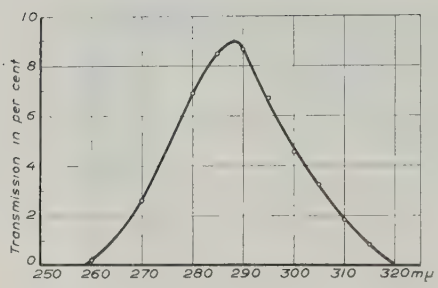

Fig. 16. The spectral transmission of the filter for isolation of the range 260—320 mμ.

factor for this error can be derived. Later these relations were known for the LK 120 lamp, and the correction factor was calculated to be 0.9. The radiation flux in the wavelength range mentioned should then be 4.3 watts. This value agrees well with the sum of the values obtained for each spectral line by the photographic spectroradiometric measurements described below (see Table 2).

The composition of the filters used to select the wavelength band 260—320 mμ is seen from Table 6 (KREFFT and RÖSSLER, 1936). The solution filters were kept in quartz cuvettes. The spectral transmission of the filter combination actually available for the range 260—320 mμ was controlled in the usual photographic spectroradiometric way (see p. 90), with the result given in fig. 16. The transmission curve obtained is in good agreement with the original curve given by KREFFT and RÖSSLER.

The filter combination has also some transmission in the red and infrared, which is easily shown by measuring an incandescent lamp. This source of error in the measurement of ultraviolet radiation can be avoided by making a supplementary measurement with a common glass plate combined with the filters. The difference of the readings with and without this glass plate, corrected for the loss due to reflection, gives a measure of the ultraviolet radiation (method of differential measurement). For mercury lamps this correction may, however, be neglected.

The measuring equipment available included two other filter combinations, intended to select the ranges 320—355 mμ and 350—410 mμ, with the compositions given in Table 6. In the spectroradiometric control of the transmission limits given for these filters it was found, however, that the filter for the band 320—355 mμ also had a considerable transmission in the short-wave range 260—270 mμ, which limits its usefulness. The *long-wave UV-filter combination*, where the transmission limits were checked to be 350—400 mμ, has been used for measurements of the strong mercury line at 366 mμ. As compared with the UV-Normal, the energy flux of this wavelength from the LK 120 lamp was 3.9 watts. This is the value given in Table 2.

This filter method has proved valuable for making rapid estimations of the approximate energy distribution of different radiations and to look for variations between different specimens of the same lamp. A serious, but inevitable disadvantage is that it does not give any information about the relative energy distribution within the important range 260—320 mμ. A displacement of the relative wave-

Table 6. *Composition of Filters for Isolating Different Spectral Regions of Ultraviolet Radiation.* (From KREFFT and RÖSSLER, 1936.)

260–320 mμ	320–355 mμ	350–410 mμ
SCHOTT filter UG 5	SCHOTT filter UG 5	SCHOTT filter UG 2
BÄCKSTRÖM filter	BÄCKSTRÖM filter	» » GG 2
Picric acid (10 mm, 0.063 %)	Nitric acid (10 mm, 0.3 N)	Cupric sulphate (10 mm, 5.7 %)

The BÄCKSTRÖM filter: $\left\{\begin{matrix} Ni\,SO_4 \cdot 7\,H_2O & 49.2\,\% \\ Co\,SO_4 \cdot 7\,H_2O & 14.1\,\% \end{matrix}\right\}$ thickness 20 mm.

length intensities in this range may change the relation of the erythema- to the ophthalmia-efficiency and probably also influence the yield of vitamin D. These factors made necessary more accurate measurements of the ultraviolet spectrum.

The equipment was easily adapted for measurements of the *luminous powers* of different lamps. The filters and the photocell were exchanged for a Weston Photronic cell, with the spectral sensitivity curve corrected by filters in accordance with the normal luminosity curve of the eye. The readings were calibrated in lumens after standardization against an incandescent normal-lamp.

The Spectroradiometric Method[1].

The more accurate determinations of the spectral energy distribution below 350 mμ, in the radiation from different UV-sources, also in absolute units, have been made on the principle of *heterochromatic photometry* (see, e. g., SAWYER, 1945), with the UV-Normal as the reference standard source.

Procedure. Series of spectrograms of the horizontally emitted radiation from the test lamp and the standard lamp, for the same distance, were taken successively with a quartz spectrograph (FUESS, Berlin) on spectral process plates (Ilford, or Agfa Autolith), with the exposure time increasing in logarithmic steps. The optical densities ($= \log 1/d$, $d =$ transmission factor) of all the spectral lines in every spectrogram were then measured with the aid of a special ZEISS microphotometer. For each line the density curve was plotted on semi-logarithmic paper, with the exposure time on the logarithmic abscissa and the density on the ordinate. In such a diagram the curves be-

[1] For these measurements instruments were made available by the Royal Institute of Technology, Department of Physics, Stockholm.

come straight lines over a wide exposure range, the gradient varying linearly with the spectral contrast factor of the plate emulsion. The mutual relation between the intensity of a line in the test lamp and the normal lamp radiation is then obtained as the reciprocal of the exposure times which give the same density on the straight part of the curve.

To avoid any influence of the development of the plates, the density curves compared were always taken from the same plate or from plates handled simultaneously. The galvanometer scale of the microphotometer was calibrated to give the densities at once and the readings were directly plotted on the semi-logarithmic diagrams.

As the spectral intensities of the UV-Normal radiation are given in absolute units, the ratios obtained for the test-lamp radiation could be transformed to absolute units, the accuracy mainly depending on the reliability of the standard lamp.

Evaluation of spectral radiant flux. The data obtained in this way give the density of radiant energy for each spectral line in the horizontally emitted radiation. To get from these data the total energy (flux) of each wavelength emitted by the source the *intensity distribution curve* must be considered. This was determined, as the average of radiation of wavelengths below 315 mμ, by means of the filter-difference method described below. The result in the case of the LK 120 lamp is plotted in the polar diagram of fig. 9 (p. 67). The intensities (I) at different angles, being the averages of several meridians, are expressed as percentages of the horizontal intensity. The flux (F) between the angles θ_1 and θ_2 is then obtained from the following formula (cf. Boast, 1942):

$$F_{\theta_1-\theta_2} = 2\pi \int_{\theta_1}^{\theta_2} I \cdot \sin\theta \cdot d\theta$$

or, if the mean value of the intensity between the limits θ_1 and θ_2 is taken as a constant of the integration,

$$F_{\theta_1-\theta_2} = 2\pi\, I_{mean} \Big| (\cos\theta_1 - \cos\theta_2) \Big|_{\theta_1}^{\theta_2}$$

Every 10 degree zone from 0° to 180° was treated in this way, the sum giving a relative measure of the total flux in the spectral region below 315 mμ emitted by the source. As the horizontally emitted radiation is known in absolute units for each wavelength, the total flux of each wavelength can also be expressed in absolute units. It has been assumed that the distribution curve is similar for all the wavelengths below 315 mμ.

In this way the values given in Table 2 were obtained.

This method of getting the spectral energy radiation of a source is rather laborious, as the density curves of about 30 spectral lines in

the range below 350 mμ have to be obtained, each of which from at least five density readings. Obviously the method is not suitable for routine measurements. Because of that, and as these measurements are of such fundamental importance in testing sources for UV-illumination, the following simple but approximate method may be recommended.

A Semi-quantitative Spectrographic Method.

This method, which has been developed during the present investigation, is based on the principle of varying the exposure on the photographic plate of a spectrograph, in such a manner that the threshold of macroscopic blackening for different intensities is reached at different heights of the plate. This aim has been realized by moving the plate past the exit slit of the spectrograph with a velocity, varying during the time of exposure according to an exponential function. The same result may also be obtained by using a logarithmically cut sector rotating before the entrance slit, as described in standard handbooks, (see, e. g., Lewis, 1946; Sawyer, 1945), but then the quantitative spectrogram on the plate is not higher than the length of the slit. By the plate-moving method the total height of the plate can be utilized.

The *theory of the method* is as follows. From the reciprocity law of the photographic plate emulsion it is assumed that the product of radiant intensity (E) and exposure time (t) is a constant for the threshold blackening,

(1) $$E \cdot t = c_1$$

The spectral plate is moved upwards, past the exit slit of height a, with the decreasing velocity $dz/d\tau$, where z is the scale of the plate height, measured from the initial stationary spectrogram, and τ the time for the displacement. At the end of the displacement the plate has moved the distance $z = k$, i. e., k is the height of the utilized part of the spectral plate (see fig. 17).

The velocity should vary in such a way that the threshold exposure $E \cdot t = c_1$ should be exceeded at a point where the distance $(k—z)$ is directly proportional to the intensity E, thus,

(2) $$(k — z) \cdot t = c_2$$

If the exposure time t, at $z = a$, is taken as unity, it follows that $k — a = c_2$, or generally

(3) $$E \cdot t = k — a$$

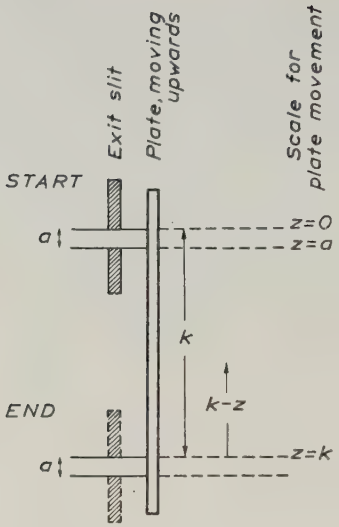

Fig. 17. Schematic representation of the semi-quantitative spectrographic method. The upward movement of the plate may be imagined as a downward movement of the slit. See text.

The exposure time t is at every point dependent on the velocity of the plate past the slit according to

$$t = \frac{a}{dz / d\tau} \tag{4}$$

By substituting $c_2 = k - a$, and the value of t from above, in eq. (2), it follows that

$$\frac{a \cdot d\tau}{dz} = \frac{k - a}{k - z} \tag{5}$$

from which z is obtained:

$$z = k\,(1 - e^{-\frac{a}{a-k}\tau}) \tag{6}$$

The differential quotient $dz/d\tau$ of this equation is the velocity at which the plate should move past the exit slit.

The *practical arrangement* is seen in fig. 18. The curve of eq. (6) is solved numerically between the limits $\tau = 0$ and $\tau = 200$ seconds, with $k = 70$ mm (utilized height of the plate) and $a = 2$ mm (height of exit slit). This curve has been cut in a metal plate in the form of a slot, into which a small wheel is placed. The two ends of the axis of the wheel are attached by two arms to the plate-holder of the spectrograph. The metal plate with the slotted curve is moved by a small motor with a constant velocity v above the plate-holder,

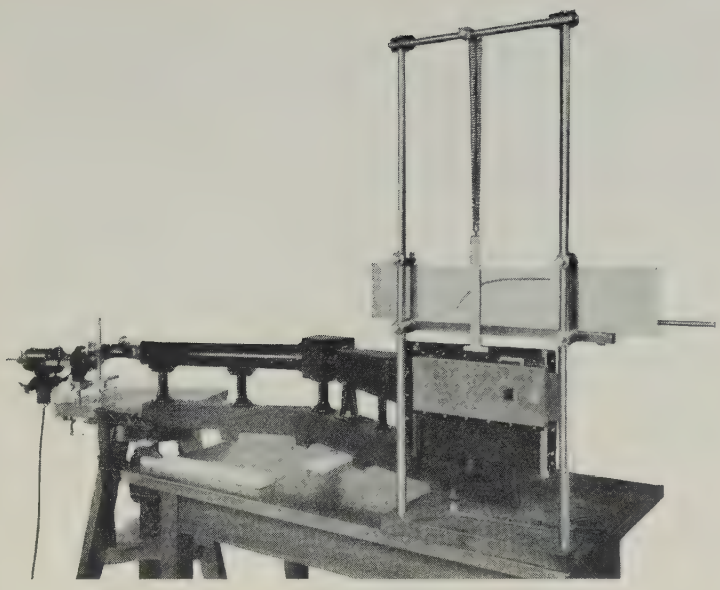

Fig. 18. The spectrograph equipped with the arrangement for semi-quantitative spectrography. A rotating sector is placed in front of the spectrograph.

and the wheel with the attached plate-holder runs up along the curve, pulled by a spring (see fig. 18). The time τ in the equations above is then given by the ratio L/v, where L is the length of the horizontal projection of the metal curve, and v is the adjustable speed of the movement of the metal plate.

The intensity of radiation on the entrance slit suitable for the procedure may be varied by the distance of the source, or by a rotating sector placed in front of the spectrograph. A pre-exposure is first made, with the plate at the lowest position, giving a narrow spectrogram at the upper part of the plate. Then the motor is started, and the plate moves upwards. At the end of the displacement the exposure is continued until a distinct after-spectrogram is obtained at the bottom of the plate.

From the developed plate a print is first taken on a hard lantern slide or photographic paper, and then a new print is made from the first one. *A line spectrum is then seen as black lines of different heights, corresponding to the different intensities.* The heights should be read from the upper end of the after-spectrogram. To get a very distinct upper limit of the lines on the prints, it was found suitable

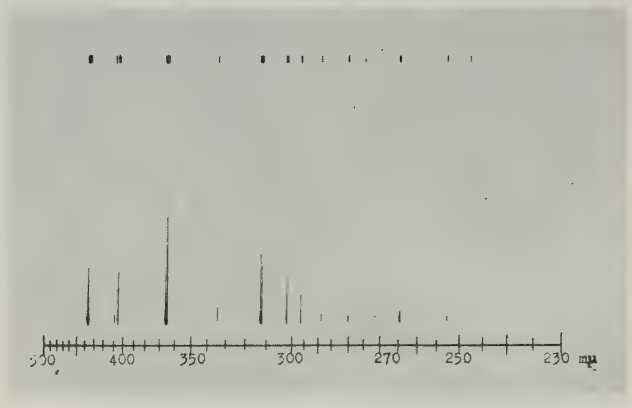

Fig. 19. A semi-quantitative spectrogram of the LK 120 lamp radiation.

to use a wet printing procedure from the first paper print to the second paper. In this way the spectrograms of figs 19—21 were obtained.

The first limitation of the accuracy of the method is obviously that the reciprocity constant (c_1) is not constant over the entire spectrum. This makes comparisons between different wavelength intensities on the same spectrogram approximate. For ordinary spectral process plates the sensitivity, however, is rather constant in the wavelength range 250—400 mμ, i. e., the region of interest for most biological purposes (see MEES, 1931; and for Autolith plates see SEITZ and MEYER, 1942). This error may be avoided by comparison for each wavelength with a standard lamp spectrum obtained in a similar way.

For a given band of wavelengths, the energy content is approximately proportional to the *area* of the blackening. As the wavelength scale in prism spectrographs is spread out towards shorter wavelengths, the actual *height* of the blackening in such semi-quantitative spectrograms becomes smaller for the same spectral energy content at shorter wavelengths. Accurate readings of the semi-quantitative spectrograms must then be made by means of *area measurements* instead of height measurements. The area measurement can be conveniently carried out by reflection or transmission determinations of the selected parts of the paper prints.

The photographic treatment of the plates, especially the steps in the reproductions, involve further errors in the method. It has been

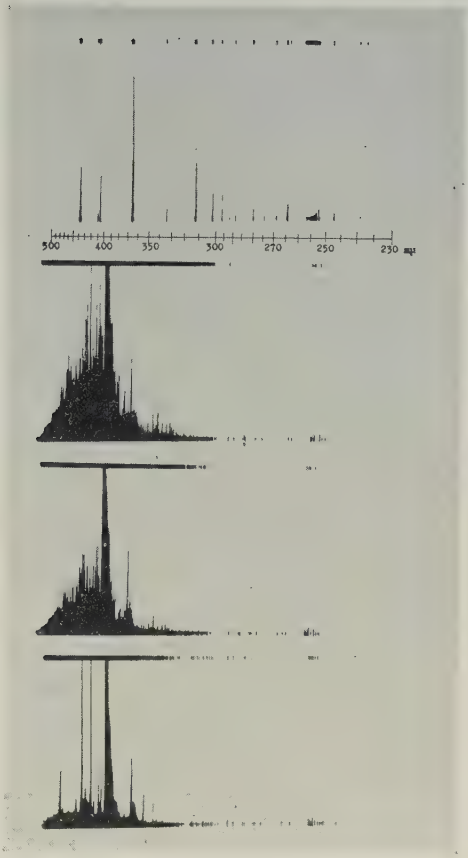

Fig. 20. Semi-quantitative spectrograms of the UV-Normal lamp radiation (uppermost spectrogram) and different types of carbon arcs (Spectram, Stockholm).

found, from series of measurements of different radiant sources, that the error of the method with careful handling is of the order of magnitude of $\pm$ 25 per cent. For most biological purposes such an accuracy is sufficient.

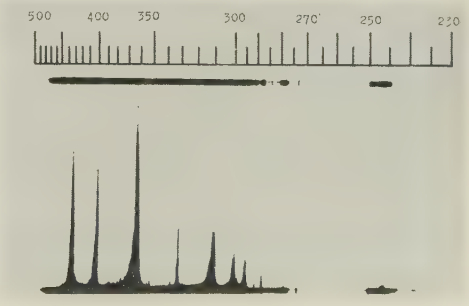

Fig. 21. Semi-quantitative spectrogram of a high-pressure quartz mercury arc (HBO 500, Osram).

Measurements of Spectral Transmission and Reflection[1].

The determinations of the ultraviolet absorption or transmission curves of different filters and glasses used in the investigation have been made in the usual spectroradiometric way, by means of a Zeiss double-sector spectrometer (Spectrograph Qu 24), with a Hüfner quartz prism as the beam-splitting device. A full description of the method employed is found, e. g., in Heilmeyer (1943).

The same arrangement was also used for the spectral reflection measurements of painted and otherwise treated surfaces. A circular plate covered with evaporated magnesium oxide was attached to the centre of the test plate, and used as standard for the measurements. This combination was rotated in front of the spectrograph and illuminated from the side with a mercury arc quartz lamp. The standard MgO-plate was projected into the slit of the prism to form one beam, the intensity of which was varied with the adjustable sector. The beam reflected from the test plate was reduced to a constant intensity by the other part of the double-sector. The density comparisons were estimated by the eye.

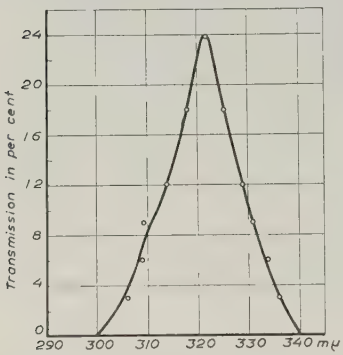

Fig. 22. Spectral transmission of the silvered quartz plate used for ultraviolet photography.

A striking illustration of the difference in ultraviolet-reflecting power of different surfaces was rapidly obtained by *ultraviolet photography*, using a mercury arc quartz lamp as the light-source (see fig. 12). The glass lens of the camera was exchanged for a quartz lens, but a stenopaeic hole instead of the lens was also satisfactory for this purpose. A quartz plate, covered with a thin layer of silver according to the method of Brashear (see Strong, 1944), in combination with a Schott UG 5 filter, was placed in front of the camera. The spectral transmission of the silvered quartz plate is shown in fig. 22 (cf. von Angerer, 1944).

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[1] Most of these measurements were carried out at the Military Research Institute, Department I, Stockholm. The reflection measurements were made in collaboration with Dr O. Quensel at this Institute.

Measurements of Ultraviolet Radiant Intensities.

The determinations of actual surface intensities of visible and ultraviolet radiation have been made with *selenium barrier-layer photocells*, covered with suitable filters, in connection with a low-resistance galvanometer (mainly the Multiflex). The readings obtained by such a device are functions of the spectral energy distribution of the radiation, the spectral transmission of the filter and the spectral sensitivity of the photocell. With suitable filters it is sometimes possible to imitate the spectral sensitivity curve of a special photochemical or photobiological process, as for instance the luminosity curve is imitated in colour-corrected illumination meters. The readings are then directly obtained in weighted values. Otherwise, adequate comparisons between different readings are only allowable when the spectral energy distributions of the compared radiations are identical, or are known in relative values for both radiations (see KREFFT, 1942 b). Another limitation of these photoelectric measurements is that the photocell response does not correctly follow the cosine law for oblique incidence (see LARCHÉ, 1942). In common illumination measurements allowance for this error is, however, usually not made.

Unfortunately, there are no glass filters available for the selective isolation of ultraviolet radiation below about 315 mμ. Special phototubes exist which have their long-wave sensitivity limit in this region, making them suitable devices for such measurements (cf. p. 20). There is, however, a possibility to make use of selenium cells for these measurements also, namely by the *filter-difference method*. A survey of the applicability of this principle is given by SEITZ and MEYER (1942, 1943) and HENSCKE and SCHULZE (1942). In this investigation the following simple method was used.

For every intensity determination a reading was first taken with the exposed photocell covered by a thin quartz plate, and then another reading with the photocell covered by an ordinary glass plate. The difference of these readings measures the radiation which is transmitted by the quarz plate but not the glass plate (see fig. 23). The quartz plate is used in order to give equal reflection conditions. The long-wave limit of the device used was at about 355 mμ, as found by the transmission measurements of the plates. In measuring mercury radiation, where the range below this limit only contains the weak line at 334 mμ before the strong lines about 300 mμ and shorter, *the response of the device becomes mainly a measure of the biologically important range around and below 300 mμ*. Ordinary incandescent light does not give any perceptible difference-reading.

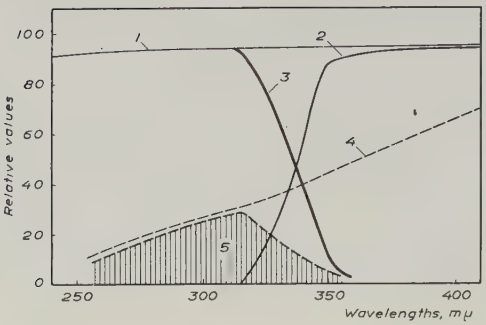

Fig. 23. The principle of the filter-difference method. 1 = transmission of the quartz plate; 2 = transmission of the glass plate; 3 = difference of 1 and 2; 4 = spectral sensitivity of the photocell; 5 = resultant spectral sensitivity of the filter-difference equipment.

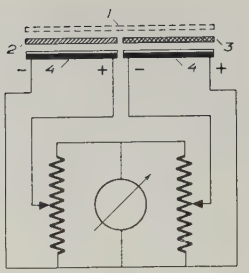

Fig. 24. Circuit arrangement of the balanced photocells for direct filter-difference readings. 1 = glass plate for zero adjustment; 2 = quartz plate; 3 = glass plate; 4 = photocell.

Instead of making the two readings successively it is possible to balance such a quartz-covered photocell against a glass-covered one and to *measure the difference directly* (see Müller, Garman, and Droz, 1946). As it was found difficult to find two photocells sufficiently equal for this purpose, a large selenium cell was divided into two exactly equal halves, connected according to the wiring diagram of fig. 24. The zero adjustment of the device was made with a thick glass plate covering both halves of the selenium cell.

By such devices the determinations of the ultraviolet distribution curves of figs 9 and 11 and the measurements of the ultraviolet intensities prevalent in the experimental installations have been carried out.

CHAPTER 8.

A Comparison with Daylight Ultraviolet Conditions.

The purpose of the studies reported here was to find out the approximate relations between the artificial radiation climate obtained with the UV-illumination system and the natural outdoor radiation conditions in Scandinavia, with *special reference to antirachitic ultraviolet radiation.* The studies carried out are purely theoretical and do not intend to give more than a general picture of the subject.

Experimental investigations of the radiation climate of the Scandinavian Peninsula are reported by Aurén (1939, 1942), but these studies do not include the short-wave part of the ultraviolet spectrum.

From the great number of investigations of the daylight content of antirachitic ultraviolet radiation, i. e., radiation of wavelengths shorter than 313 mμ, (for literature see Büttner, 1938; Ives and Gill, 1937), the first general conclusion is that this short-wave spectral component varies to a much greater extent than the visible and infra-red radiation by *changes of the sun elevation* and also the *altitude above sea-level*. The short-wave limit is spectrographically found to be from 290 to 315 mμ, depending on the sun elevation (see Büttner, 1938). In an extensive investigation Tisdall and Brown (1931) showed that when rachitic rats are exposed for two hours to noon daylight there is a marked antirachitic effect only when the sun is more than 35 degrees above the horizon. Mayerson and Laurens (1930, see also Laurens and Mayerson, 1933) have given further evidence of the marked seasonal variation of the antirachitic effect of sunshine.

Another general conclusion of importance is that for medium and low elevations of the sun the *diffuse sky radiation* contributes considerably *more* than the direct sun radiation to the intensity of this spectral component at the surface of the earth. This has already been pointed out in the pioneer work of Dorno (1919). The biological importance of sky radiation is experimentally proved by Mai (1938, 1939).

The general validity and applicability of the different investigations carried out are, however, in many cases limited, because the indicating or integrating instruments employed have not been sufficiently well-defined with respect to the spectral sensitivity and to the correct response to sky radiation. As the short-wave limit of the sun's intensity spectrum is very abrupt, the intensity at 340 mμ for 40° sun elevation being about 100 times that at 300 mμ and 2 000 times that at 295 mμ, *the long-wave spectral sensitivity limit* of the measuring device is of decisive importance for the results obtained. Considerable sensitivity above 313 mμ is, for instance, a disadvantage of the UV-Dosimeter of I. G. Farben which has been widely used in Europe, and with which investigations have been made for many different localities and latitudes (see Büttenr, 1938; Landsberg, 1937; for northern latitudes Sydow, Riemerschmid, and Tiedemann, 1939).

It seems, however, possible to obtain a general survey of the geographical and seasonal variations of the short-wave ultraviolet, without referring to any special measuring device, from the measurements of the actual spectral energy distribution, in absolute units, of the extreme ultraviolet of the solar spectrum, recently carried out at the *Bureau of Standards, Washington,* by COBLENTZ and STAIR (1936 a–b). The principle of their extensive investigations has been to calculate, for different elevations of the sun, the exact energy distribution below and including 313.2 mμ from a set of simultaneous measurements with photoelectric and thermoelectric devices of somewhat different spectral sensitivity within this wavelength range. *The following calculations are mainly founded upon the average data of these papers.* It is assumed that a given air mass causes the same depletion of the radiation at the Scandinavian latitudes as at the Washington latitude. The calculations refer only to sea-level.

O'BRIEN (1943) has published calculations of the annual and daily variations of the antirachitic, erythemal and bactericidal efficiency of solar radiation, in relative values, for the latitudes 33, 38 and 43 degrees, using approximately the same principles of calculation as have been applied here. His calculations refer only to the intensity variations, while the calculations reported here also include the *dosage* variations. To the extent to which they are comparable the agreement seems satisfactory.

The Relation of UVE-Intensity to the Sun's Elevation.

From the tables and diagrams given in the papers of COBLENTZ and STAIR the diagram in fig. 25 has been calculated and plotted, showing how the average intensities of different wavelengths below 315 mμ in the solar radiation vary with the mass of air traversed, i. e., the elevation of the sun. The fact that the plot of the decrease of intensity in the semi-logarithmic diagram is a straight line shows that the absorption in the atmosphere follows in the main an exponential law. The thickness of the mass of air traversed by the rays (m) is found from the sun's elevation (h) by the formula

$$m = \frac{1}{\sin h}$$

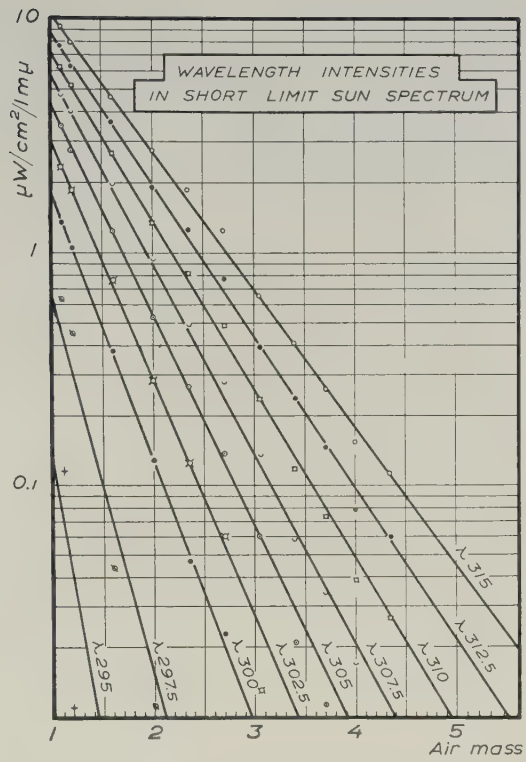

Fig. 25. The intensity depletion of different wavelengths in the short-wave end of the solar spectrum with increasing ray length through the atmosphere (air mass). The unit air mass is the length of the path through the atmosphere if the elevation of the sun is 90° (cf. fig. 26). The diagram is computed and plotted from data given by Coblentz and Stair (1936 a–b).

i. e., the mass of air is measured in no. of atmospheres, with the zenith atmosphere ($h = 90°$) as unity (cf., e. g., Conrad, 1942). The general mathematical expression of the curves in the diagram is then

$$I_{m\lambda} = I_{o\lambda} \cdot (q_\lambda)^m$$

where $I_{m\lambda}$ = the intensity of wavelength λ for mass of air = m,
$I_{o\lambda}$ = the corresponding extra-terrestrial intensity ($m = 0$),
q_λ = the transmission coefficient $\left(\frac{I_{1\lambda}}{I_{o\lambda}}\right)$ for the wavelength λ.

The curves given are valid for the intensities perpendicular to the direction of the sun's radiation and only for sea-level. Sky radiation is not included.

Table 7. *Wavelength Coefficients for the Evaluation of UVE-Radiation.*

Wavelength mμ	Erythemal factor I.C.I.	Antirachitic factor		UVE-coefficient adopted
		Knudsen-Benford	Bunker-Harris	
295	0.98			1.0
297.5	1.0	1.0	1.0	1.0
300	0.83			0.8
302.5	0.55	0.48	0.47	0.5
305	0.33			0.3
307.5	0.20			0.2
310	0.11			0.1
312.5	0.03	0.01	0.0	0.02
315	0.01			0.00

Every ordinate in this diagram includes values of the average spectral energy distribution, in absolute intensity units, for the corresponding air mass, i. e., sun elevation, and may be used as a nomogram for the equation given above. By weighting the *energy distribution curves* plotted from this diagram against the *action spectrum* of a photobiological response, a series of *product curves* of weighted spectral intensities is obtained for the different sun elevations. The surface integrals of the product curves give the total intensity of weighted incident energy, expressed as the equivalent intensity of the reference wavelength in the action spectrum (see fig. 3, p. 47).

From the point of view of human physiology the *antirachitic effect* and the *erythema effect* are of special interest. The relative shapes of the action spectra for these two effects happen to coincide almost exactly for wavelengths longer than 295 mμ, i. e., the short-wave limit of the solar spectrum, if the action factor for the wavelength 297 mμ is taken as unity for both these curves (see fig. 4, p. 51). For the purpose of the following calculations an *average action spectrum* was adopted for the biologically-effective radiation (UVE) in the solar radiation. The wavelength coefficients selected are given in Table 7. Wavelengths longer than 315 mμ have not been given any weight, as they do not possess any antirachitic properties. They have, however, a slight erythema effect, or rather a tanning effect, on human skin, which may contribute about as much to the total tanning effect of solar radiation as the wavelengths below 315 mμ (see p. 51). *The UVE-values obtained by the action spectrum adopted here*

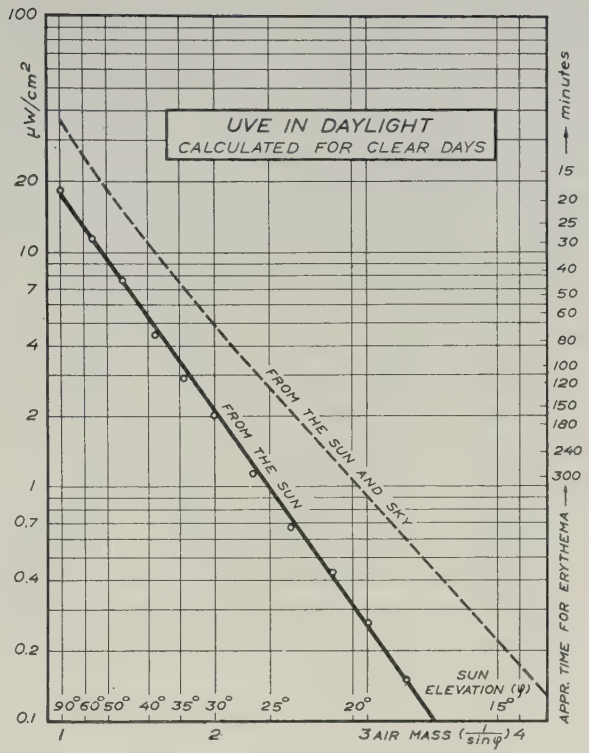

Fig. 26. Calculated intensities of erythemally-weighted ultraviolet radiation of wavelengths below 315 mμ (UVE) in solar radiation (perpendicular to the rays) and of sun and sky radiation on a horizontal surface at different elevations of the sun.

will then be somewhat too small with regard to the skin-tanning property of the radiation, but will fit the antirachitic efficiency closely.

Fig. 26 shows the UVE-intensities obtained in this way as a function of the mass of air. As expected, it also gives a straight line when plotted on a semi-logarithmic diagram. The unbroken curve is valid for the *solar radiation*, perpendicular to the direction of the rays. It corresponds to an effective transmission coefficient (q) of about 0.10.

The relative contribution of *sky radiation* to the short-wave ultraviolet intensity at the earth has been measured by, among others, Büttner (1938) and Luckiesh, Taylor, and Kerr (1939). In spite of the different methods employed, the results are in almost perfect agreement when expressed in a similar way. *The ratio of sky radiation to sun radiation* on a horizontal surface equals unity at sun elevations

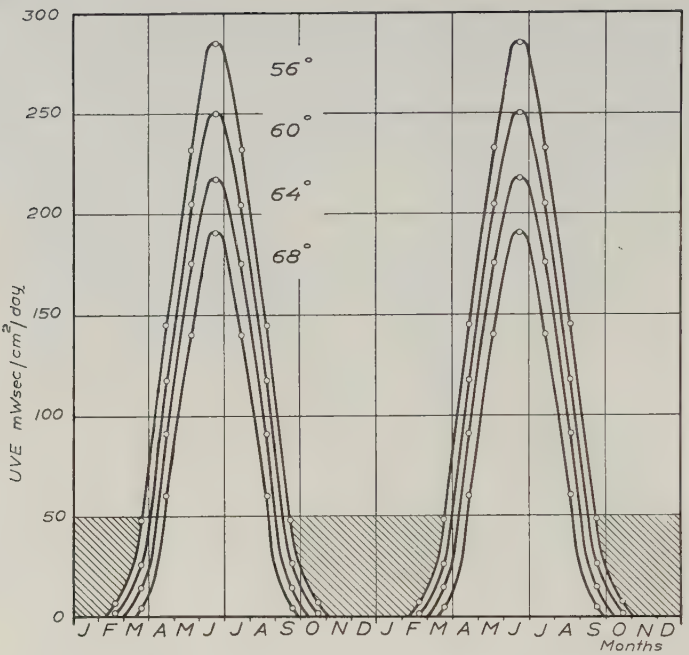

Fig. 27. Calculated daily amounts of UVE arriving at a plane perpendicular to the solar radiation for different seasons of the year and at different Scandinavian latitudes. The shaded level denotes the amount (dosage) required for producing a slight degree of tan on the average unpigmented human skin. The corresponding curves for sun and sky UVE incident on a horizontal plane are practically identical if the ordinate scale is doubled.

above 70 degrees, provided that the air is clean, and rises to about 10 at a sun elevation of 20 degrees. By using the mean quotient obtainable from these investigations for every sun elevation, the UVE-intensity on a *horizontal surface* from *both sun and sky radiation* was calculated, with allowance of course for the cosine law for the direct sun radiation. The result is shown by the broken curve of fig. 26.

It is seen from this diagram that the UVE-intensity 1.5 μW/cm² obtained by the artificial UV-illumination system in the experimental schoolrooms corresponds to the UVE-intensity of direct solar radiation for a sun elevation of about 30 degrees above the horizon, or to the intensity falling upon a fully exposed horizontal surface on a clear day for the sun elevation 20—25 degrees. It may be mentioned, that the midsummer sun elevation in the south of Sweden reaches a maximum of about 55 degrees, and in the north of Sweden about 45 degrees.

The corresponding exposure times calculated to produce a threshold erythema for the different UVE-intensities are given by the ordinate on the right of fig. 26. The threshold dosage was presumed to be 20 mWsec/cm². The data are in good agreement with similar time values given by Büttner (1938) for the exposure necessary to produce a slight tan of normal skin for different sun elevations. The intensity values of the diagram agree well with some corresponding data also given by Luckiesh and Taylor (1945).

Daily Dosage of UVE at Different Seasons and Latitudes.

From the photobiological point of view the intensities of UVE-radiation in daylight are of less interest than the *daily dosages* available for different seasons and latitudes. Actual measurements of the daily amount of tanning-active ultraviolet radiation have recently been made during a six year continuous record by Luckiesh, Taylor, and Kerr (1937, 1939, 1944; see also Luckiesh, 1946), at a latitude of 41.5° N. The calculations made in the present investigation mainly refer to Scandinavian latitudes, but for the comparison they have also been made for lower latitudes.

With the aid of the diagram in fig. 26 and of the curves available for the apparent course of the sun across the sky on different days of the year and in different latitudes, the *daytime variation curve* of the UVE-intensity was plotted in diagrams for six pairs of corresponding days in the year. *The surface integral of such a curve gives the total UVE-energy* (*UVE-dosage*) *incident for that cloudless day.* Fig. 27 summarizes these integrated data obtained for different seasons and different Scandinavian latitudes, with respect to the *sun radiation* perpendicular to the rays (sky radiation not included). Similar day-dosage curves were also calculated for *sun and sky radiation* on a horizontal plane, and it was found that the course of these latter curves was in almost perfect agreement with the curves in fig. 27 if only the ordinate scale were doubled.

It is seen from the figure that there is *practically no antirachitic radiation* (*UVE*) *at all reaching the earth's surface during 4—6 months of the year, at the Scandinavian latitudes.* With the UV-illumination the daily exposure was maintained during the winter at a level of about 20 mWsec/cm² of UVE-radiation.

Annual Dosage of UVE at Different Latitudes.

The surface integrals of the day-dosage curves of the year (fig. 27) permit a computation of the theoretical value of the *total UVE-energy maximally available* during a presumed cloudless year. Such values, including *UVE-radiation from sun and sky reaching a horizontal surface* are calculated for different latitudes, with the result shown in fig. 28. The broken line indicates the total heat insolation, in relative values, for a horizontal surface, given as annual averages for clear days (see CONRAD, 1942). *The much greater influence of the geographical latitude on the amounts of ultraviolet radiation reaching the earth as compared with the total heat radiation is evident from the figure.*

The total annual UVE-radiation calculated in this way for the latitude of 40° is, as seen from fig. 28, 125,000 mWsec/cm². This value should be compared with the average value actually found in the integrating photoelectric measurements of LUCKIESH, TAYLOR, and KERR, mentioned above, which was 3,000 E-viton hours, or 110,000 mWsec/cm² of tanning-effective radiation. Allowing for the mean cloudiness and the fact that their measuring device was also somewhat sensitive for wavelengths longer than 315 mμ, the agreement is surprisingly good.

The calculations reported here are obviously only of a general nature, giving an estimation of the theoretical maximum values of UVE-energy available at different latitudes and different seasons. The *real ultraviolet radiation climate of a locality* is dependent upon many other factors, such as the cloudiness, the albedo of the earth's surface, the altitude, and local and seasonal variations of the transmittance of the atmosphere. The content of ozone in the atmosphere exerts a great influence on the spectral energy distribution of the short-wave ultraviolet spectrum, and this content is known to vary considerably from day to day. The effect of this is clearly demonstrated in the calculations of O'BRIEN (1943). In conclusion, however, the deciding factor from the hygienic point of view is the degree to which the outdoor radiation climate is really utilized by human beings.

The effect of cloudiness and snow. — It is found by BÜTTNER that cloudiness generally diminishes the ultraviolet radiation to a less extent than visible light and heat radiation. The spectral composition in the UVE-range is not al-

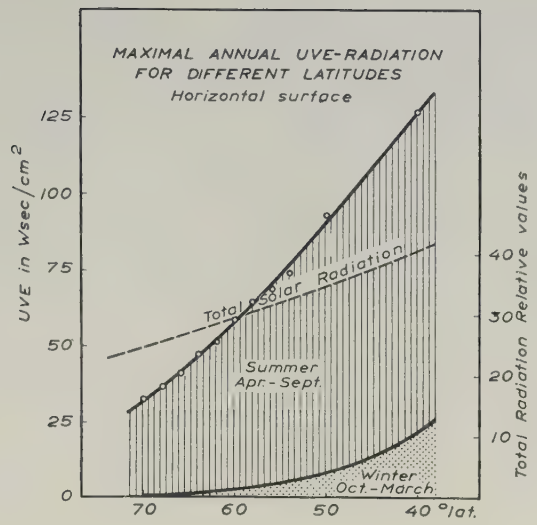

Fig. 28. Calculated amounts of UVE reaching a horizontal surface directly from the sun and entire sky for a presumed cloudless year at different latitudes. The curve of total solar radiation gives the same data (in relative units) for the total of ultraviolet, visible and infra-red radiation.

tered by clouds or fog (Coblentz and Stair, 1935). When the sky is entirely covered by clouds (cloudiness 10) the UVE-intensity at the earth is diminished to about 50 per cent of the corresponding clear sky intensity, as measured with the UV-dosimeter (see Büttner, 1938). The average number of hours of sunshine during the summer months in Sweden, according to Ångström (1946), is 45—50 per cent of the possible number. It could then be expected that about three quarters of the calculated value of the maximal annual UVE-energy reach the earth in Sweden, i. e., about 36,000 mWsec/cm². During the winter months the average cloudiness is still greater, but on the other hand the *snow-cover* causes at least a doubling of the mean radiation intensity by reflection (see Büttner, 1938).

An obvious consequence of the data obtained by these calculations is that the use of special *ultraviolet-transmitting glass in windows* in order to get an improvement of the indoor radiation climate is futile during the winter, at least at the latitudes of Scandinavia. The ineffectiveness of such devices for general use was pointed out long ago by Clark (1928) and Kollath (1929), see p. 36. Hence the only way to attain this purpose is to make use of artificial sources of ultraviolet radiation.

Table 8. *Intensities of Visible and Ultraviolet Radiation in Daylight (Clear Days). Estimated Values.*

Component of Radiation	Sun Elevation 60°		Sun Elevation 30°	
	Direct Sun	Sky	Direct Sun	Sky
Light	100,000 lux	17,000 lux	75,000 lux	15,000 lux
UV 400—315 mμ	4,000 μW/cm²	?	2,500 μW/cm²	?
UV below 315 »	55 »	60 μW/cm²	15 »	20 μW/cm²
UVE »	12 »	13 »	2 »	3 »
UVK »	6 »	7 »	1 »	1.5 »
UVX »	1.6 »	2 »	0.3 »	0.5 »
UVG	12 »	(10)	4 »	(4)

The Average Daylight Ultraviolet Climate.

For the comparison of the outdoor "ideal" radiation climate with the artificially created radiation climate indoors see Table 8 which is given in the same form as Table 5, p. 77. The illumination values are according to LUNELUND (1935), the data for long-wave ultraviolet are taken from the measurements of AURÉN (1939) and the data for short-wave ultraviolet from the measurements of COBLENTZ and STAIR used above. The weighted intensities given for UVK, UVX and UVG are calculated in the same manner as was applied to UVE in the calculations reported above. The action spectra for these biological effects in the long-wave ultraviolet range (315—400 mμ) are, however, in general not so well-known as for the shorter wavelengths, which makes these values in the table rather uncertain. For both UVK and UVX, i. e., the radiation injurious to the eye, the action spectra available were arbitrarily extrapolated to 315 mμ, where the long-wave limit was placed, as done previously for the UVE-radiation. The bactericidal intensities (UVG) are computed upon the basis of the action spectrum given by LUCKIESH, HOLLADAY, and TAYLOR (see LUCKIESH, 1946), which includes data as far as in the visible spectrum. In the main this curve seems to be in agreement with the findings of other authors (cf. HOLLAENDER, 1946).

A comparison between the tables indicates that *the UV-illumination offers some resemblance to the natural radiation climate at the sun elevation 20—30 degrees*, but only with respect to the biologically weighted intensities of short-wave ultraviolet. For the same erythema-effec-

tive intensity, the intensity of *long-wave ultraviolet radiation* is at least 500 times greater in the natural solar radiation than in the mercury radiation of the UV-illumination. One consequence of this, as pointed out before, is that the degree of skin-tanning of the children in the illuminated classrooms was not as high as would have been reached by the same UVE-dosage of natural sunshine.

It should be noted that the intensity of ophthalmia-producing radiation in natural daylight, calculated in this way, is comparatively high, also for sky radiation alone. The reason why the effect of this is not usually observed may be the same as that assumed for the UV-illumination, i. e., the protected situation of the eyes for overhead radiation. The risk of eye-irritation in the UV-illuminated rooms could then be expected to be not much higher than outdoors during a bright summer day.

III.

The UV-Illumination Effects.

CHAPTER 9.

A General Scheme of the Experiments.

The investigation of the physiological and hygienic effects of the supplementary ultraviolet radiation in the artificial illumination, obtained by means of the UV-illumination system previously described, has hitherto been carried out in a Secondary school and a Primary school in Uppsala during a period of three school terms (one and a half years). The organisation of the school classes involved in the experiments is shown in fig. 29. Every rectangle represents a group of about thirty children, corresponding to an ordinary Swedish school class. The ultraviolet irradiated groups are marked with shaded rectangles, the control groups with open rectangles. During the last term of investigation the non-irradiated Group III was divided into two halves, one of which was treated with a large dose of vitamin D, as indicated by the half-pointed rectangle (later referred to as *The Vitamin D Experiment*). The connecting lines indicate that the same children have been followed consecutively over more than one term. *A total of about 220 children have been involved in the experiments, 120 of which have been given ultraviolet irradiation for some period of time.*

Groups I and II and, after the first term, also Group III were composed of boys only, the other groups of both boys and girls. The age distribution was very homogeneous, with practically all 6—7 year-old children in the Primary school classes and 9—11 year-olds in the Secondary school classes. The social character of the groups can be regarded as representative of a random sample of Swedish Primary and Secondary school children and without significant differences between the several groups engaged. An interview revealed that only very few of them were having their diet supplemented by vitamin preparations during the winter.

The classrooms of Groups I—III were situated next to each other along a ground-floor corridor of the Vaksala Secondary School in

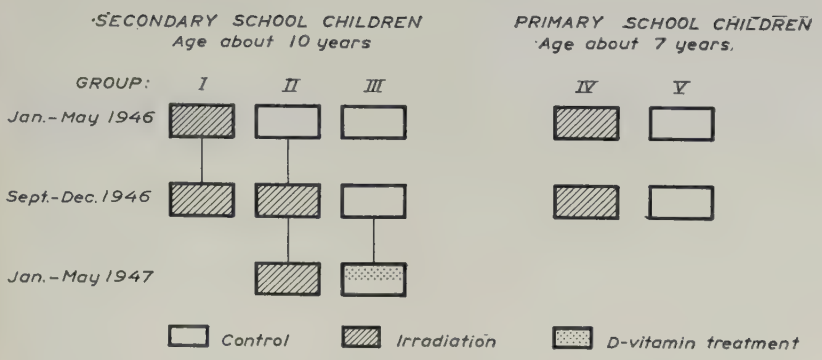

Fig. 29. The organization of the school children trial on UV-illumination. Every rectangle corresponds to a class of about 30 pupils for one school term.

Uppsala, each with four windows facing North-East and towards the playground. The opposite side of the corridor included other classrooms, not engaged in this trial. The classroom of the experimental Group IV, with Primary school children, was situated in a small private building in an outer part of the city, and no other children were taught there. The control Group V was selected from corresponding classes of the Vaksala Secondary School. The daylight illumination in all the classrooms involved in the trial was in good agreement with modern Swedish requirements (see ARNER and YLLNER, 1941).

During the first term of the investigation Group I was provided with the UV-illumination system, and in the classroom of Group II the same special fixtures were installed but without ultraviolet lamps. During the following term this room was also equipped with a complete UV-illumination system. The classroom of Group IV was provided with the complete system from the beginning. All other control rooms had common opal globe luminaires.

The investigation has included the following examinations and studies.

1. Six series of *blood analyses* on the children with regard to the following blood constituents:

the haemoglobin concentration,
the plasma level of calcium,
the plasma level of inorganic phosphorus, and
the plasma activity of alkaline phosphatase.

2. Six series of evaluation of the *physical fitness* of the children by testing with a submaximal work.

3. Determinations of the *concentration of micro-organisms in the air* in the experimental and control rooms, made by random samples during the last term of the investigation.

4. Record of the *absenteeism due to illness* among the children, supplemented with statistics of the annual course and height of the absenteeism in a number of corresponding school classes for the years 1943—47.

Records have also been made of the increase in height and weight of the children, obtained from the body measurements made in connection with the fitness tests. These measurements were, however, not made with sufficient accuracy to permit a reliable interpretation, and the material was too small to give significant differences between irradiated and control children.

The Statistical Treatments.

The statistical data of the *error of estimations* are reported in connection with the descriptions of the different methods employed. For the methods of the *blood-chemical analyses* a large number of double determinations on different specimens, and series of determinations on the same specimen, have been carried out, permitting for all methods a very exact evaluation of the random errors of the method. This error (σ_E) is calculated from the pairs of double-determinations by using the formula

$$\sigma_E = \pm \sqrt{\frac{\Sigma d^2}{2 \cdot n}}$$

where Σd^2 = the sum of the squares of the differences between the two determinations made on the same specimen, and n = the number of pairs of such double-determinations (see DAHLBERG, 1940). For the series of determinations carried out on the same specimen the error of estimation is given by the standard deviation of the series.

Special attention is also devoted to the influence of the error of the control determinations made in connection with all the series of blood analyses. The control determinations on standard solutions are used for the conversion into absolute values of the titration values or the photometer readings obtained. If M_1 = the mean reading of the series of blood determinations and M_2 = the mean reading of the series of determinations made on the known standard solution of the concentration C, the evaluated mean (M) of the series of blood determinations is obtained from the formula

$$M = \frac{M_1}{M_2} \cdot C$$

The standard error (ε_M) of this mean value M was calculated according to the formula

$$\varepsilon_M = \pm C \cdot \frac{\sqrt{M_2^2 \varepsilon_{M_1}^2 + M_1^2 \varepsilon_{M_2}^2}}{M_2^2}$$

where ε_{M_1} and ε_{M_2} are the standard errors of the mean of the blood series and the standard series, respectively (see DAHLBERG, 1940, p. 95). When ε_{M_1} is considerably greater than ε_{M_2}, which was usually the case in the analyses carried out here, ε_M may be directly replaced by $C \cdot \varepsilon_{M_1}/M_2$.

The error of estimation in the *work tests on physical fitness* was, in accordance with common use, evaluated by means of the *retest-reliability coefficient* (r_{11}), i. e., the coefficient of correlation between two administrations of the same test on a number of individuals (see GARRET, 1947). This "self-correlation" coefficient is a quantitative estimate of the importance of chance or variable influences upon the test scores owing to the method or to unaccounted day-to-day changes of the individuals. Constant errors working in only one direction do not affect the reliability coefficient. The *standard error of an obtained score* may then be obtained from the formula

$$\sigma_{1\infty} = \sigma_1 \sqrt{1 - r_{11}}$$

in which $\sigma_{1\infty}$ = the standard error of an obtained score ("standard error of measurement"), σ_1 = the standard deviation of the series of test scores, and r_{11} = the reliability coefficient of the test. This measure of the error of a single observation takes account of the self-correlation of the method as well as of the variability within the group and is the best method of expressing the reliability of a test (GARRET, p. 392). See further p. 136.

The statistical treatment of the *samples of data* in absolute values, obtained from the different kinds and series of examinations, has included the calculations of the mean value (M), the standard deviation (σ) and the standard error of the mean (ε) in the usual manner (see, e. g., KEMP, 1942).

In order to control that the material treated did not show apparent assymetry of the distribution, the frequency distribution was plotted in graphs for every sample. There was in no case significant reason to make corrections for asymmetry. In doubtful cases the χ-square test was applied (see KEMP, p. 120).

When two compatible series of data of n_1 and n_2 individuals, respectively, with the mean values M_1 and M_2, were combined to form one group, the following formulae were applied:

$$M = \frac{n_1}{n_1 + n_2} M_1 + \frac{n_2}{n_1 + n_2} M_2$$

$$\sigma = \frac{(n_1 - 1)\,\sigma_1^2 + (n_2 - 1)\,\sigma_2^2}{n_1 + n_2 - 2}$$

$$\varepsilon_M = \pm \frac{\sigma}{\sqrt{n_1 + n_2}}$$

The Reproduction of the Results.

A detailed report of the very comprehensive material collected and the statistical data of it would be rather confusing. Hence the main results are given in a kind of *statistical diagrams* as shown in figs 30—38. *Every sample of data is represented by a rectangle, the height of which gives the range where the real mean value of the sample is to be found with a probability of 90 per cent.* The width of the rectangle gives an approximate measure of the number of observations in the sample (usually about 25).

The rectangles are obtained by using the *t*-factors in the following way (cf. KEMP, pp. 90—92). The standard error (ε) of the mean of the sample, calculated in the ordinary way, is multiplied by the *t*-factor, which corresponds to a probability of 0.1 that the real mean value would be randomly situated outside the limits $\pm t \cdot \varepsilon$ around the actual mean value obtained. This means that there is a 90 per cent probability that the real mean lies within the range $M \pm t \cdot \varepsilon$, which is the range indicated by the height of the rectangles in the diagrams. The *t*-factors corresponding to this probability level and to the number of the degrees of freedom in the samples were obtained from the tables of FISHER and YATES (1946). It should be pointed out that the rectangles thus give the 90 per cent probability range of the real mean of the group independent of the number of observations in it.

These diagrams do not, however, always permit an immediate evaluation of the *significance of the differences* between the means of different groups. Assuming that there is no correlation between the groups to be compared, an idea of the significance is of course given by the vertical distance between the adjacent limits of the two rectangles mutually displaced, but an exact evaluation of the significance can only be made by application of the *t*-test on differences between the means of small samples (see KEMP, p. 103). In the special cases reported here, however, the samples to be compared within the same time-series of examination (i. e., non-correlated groups) are always of about the same magnitude both with respect to the number of observations and the standard errors of the means. From this it follows that the ranges $t \cdot \varepsilon$ are about equal, i. e., the rectangles $M \pm t \cdot \varepsilon$ are of about the same size. If this is the case, a vertical displacement of the two rectangles to be compared, just sufficient to give a free space between them, obviously gives the relation

$$M_1 - M_2 = 2 \cdot t \cdot \varepsilon$$

The t-factor of the *difference*, called t_D, is in the same special case obtained from the formula

$$t_D = \frac{M_1 - M_2}{\varepsilon \sqrt{2}}$$

These two equations combined give

$$t_D = t \sqrt{2}$$

When the number of observations in each sample is about 25 (= 24 degrees of freedom), as in most cases here, the value of t is about 1.71 (rising to 1.81 for 10 degrees of freedom), i. e., $t_D \approx 2.40$ (or, for 10 degrees of freedom, $t_D \approx 2.55$). These t_D-values of the difference correspond to a probability for a difference at random of 0.05—0.01, thus indicating a "probable" difference. Moderate disparities of number etc. between the samples do not alter this general statement. This is the reason why the probability range for the rectangles in the diagrams was chosen at the 90 per cent level. *For all cases given in the present diagrams, a displacement of two rectangles representing different groups just sufficient to give a free space between them, indicates that the difference is at the limit of the usually accepted criterion of a real, significant difference.*

With increasing space between the rectangles the probability for a real difference is rapidly increasing. In fig. 33, for instance, the difference between the means of the two samples at March 1946 corresponds to a probability of much less than 0.001 for a difference at random ($t_D = 6.3$, $n = 57$).

Of course, in doubtful cases, all the possible differences between the different groups have also been tested in full accordance with the exact formula for the t-test on small samples, before any decisive conclusions have been drawn.

This interpretation of the statistical diagrams is, however, not valid for *comparisons of two means, when the underlying observations are correlated*, i. e., when a high value in one sample is also likely to be combined with a high value in the other sample. Such a correlation may be entering when two means should be compared, obtained from the same test administered to the same subjects upon different occasions, as in the study of possible *seasonal variations*. If there exists such a correlation, which, for instance, is rather high for the scores of physical fitness, the present diagrams under-estimate the significance of possible differences when read as described above. When seasonal variations have been tested for their significance in the present investigation, the mean and the standard deviation of the series of *differences* obtained for the subjects have been computed, and the mean difference then tested on the null hypothesis with the t-test. In this way the correlation is taken into account without making the calculation of the coefficient of correlation between the samples necessary (cf. GARRET, 1947).

As, however, the diagrams just described include most of the data of interest for the purpose of this investigation in a clear form and with regard also to the statistically evaluated significances of the means, it was considered unnecessary to give a complete, detailed account of the comprehensive material.

The statistical treatment reported above is of course valid only for the random variations of the samples. It is difficult completely to avoid the appearance of systematic errors in such a wide investigation of long duration. For instance, it was not possible to have the same assistants performing the same analyses in all the series, and the influence of the personal factor was sometimes demonstrated.

CHAPTER 10.

Effects on Some Constituents of Blood.

The time scheme for, and the number of experimental subjects in the six series of blood analyses carried out are seen from Table 9.

Table 9. *Scheme of Blood Analyses.*

Time	Group I		Group II		Group III		Group IV		Group V	
	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls
Dec. 1945	27	—	25	—	9	14	6	7	—	—
March 1946	26	—	25	—	9	16	11	14	16	9
May–June 1946	25	—	24	—	9	9	11	7	11	7
Oct. 1946	29	—	31	—	29	—	13	11	14	16
Dec. 1946	25	—	30	—	29	—	12	9	13	9
March 1947	—	—	—	—	29[1]	—	—	-	—	—

[1] 15 of whom had received vitamin D.

The reason why the last series (March 1947) did not consist of all the groups was, that the children of Groups I and II were unwilling to be subjected to further venous punctures, and for Group IV the ultraviolet lamps had become inactive and new lamps were not available. The only group examined by blood analyses during the last spring term of the investigation was therefore the class partly treated with vitamin D (Group III).

The first series (Dec. 1945) did not include phosphatase analyses, and haemoglobin determinations were carried out only in Groups II and III. The reason was methodical in origin.

The Analysis Methods Employed.

The sampling of the blood.[1] The sampling of the blood was always performed in the morning when the children had just arrived at the school. Venous puncture was made with a dry sterilized syringe, and about 10 ml of blood were allowed to flow into a thoroughly cleaned and acid-washed test tube, containing 0.2 ml of a 0.5 per cent solution of sodium heparin and some glass pebbles. The samples were centrifuged within one hour after taking the blood, and after the sample for the haemoglobin determination had been withdrawn. Analyses were carried out on 15—25 samples daily during the examination periods.

According to WILANDER (1938) there is no difference except the dilution effect in the results of blood analyses on calcium and phosphatase when using heparin plasma instead of serum. This has been confirmed, also with respect to inorganic phosphorus, by experimental controls made in the present investigation.

The Haemoglobin Method. The alkaline haematin method according to WU (see PETERS and VAN SLYKE, 1931) was employed in the following manner. After thoroughly mixing the sample, 0.05 ml of the heparinized blood was collected in 5 ml of N/10 HCl, stoppered and mixed, and left at room temperature for at least 3 hours. 0.5 ml of 10-N NaOH was then added and the solution was measured against distilled water as a blank in the ZEISS visual "Stuphen-Photometer" (Pulfrich) with 1 cm cuvette and green light filter (S 50).

The standardization of the readings was made by comparisons with the carefully calibrated Authenrieth Haemoglobinometer of Dr H. ENGHOFF at this Institute, which is used as standard for a great number of Swedish haemoglobinometers (see ENGHOFF, 1937). Standardizations were made for three of the six series of analyses, and the calibration factor obtained was in all cases exactly the same.

The values are expressed in grams of haemoglobin per 100 ml of blood ("g %") No allowance has been made for the dilution due to the heparin added.

The *error of the method*, computed as the standard deviation of 20 determinations of the same blood specimen, was $\pm$ 0.17 g %, or 1.03 per cent of the mean.

The Calcium Method. The method of KRAMER and TISDALL was employed with the procedures in accordance with the description given by KING (1946). Some other methods, which are said to be more exact, were tried but found too tedious to combine with the other analyses to be carried out on the blood samples.

The N/100 potassium permanganate solution for the titration, which was diluted from the N/10 standard solution every day of the test periods, was checked in the usual manner by titration with a standard oxalic acid solution. Further, every daily series of the plasma calcium estimations were combined with estimations of a number of specimens of an exactly weighed standard

[1] This responsible task was kindly carried out by Nurse KARIN NORDSJÖ.

calcium solution of about 10 mg %, which were handled simultaneously and in the same manner as the plasma specimens. The calculation of the plasma calcium concentration, in mg %, was performed by comparison with the mean value found for the calcium standard titrations. The oxalic acid titrations were used as an additional control of the standard estimations.

The *error of the method*, calculated as the standard deviation of a series of 20 separate titrations of the same blood sample, was found to be only 0.08 mg % (0.8 per cent of the mean). The error of the standard estimations (on the standard solution) was also found to be 0.08 mg %, as calculated from the great number of double determinations carried out. This error is considerably smaller than that found by Rothlin and von Bidder (1945). The error of the mean obtained after correcting the titration values of the blood samples with the standard titration values was calculated in accordance with the formula given on p. 107.

Isolated plasma titrations sometimes gave values deviating considerably in both directions from the mean value obtained. In doubtful cases they were tested by the criterion of Chauvenet (see Mellor, 1939) before any elimination from the final statistical treatment.

The Phosphorus Method. The method employed was that of Fiske and Subbarow, with the modifications of Teorell (1931). The amount of phosphorus determinable by this method is 10—50 μg. The following procedure was applied.

From the freshly centrifuged blood sample 0.5 ml of the heparin plasma was diluted with an equal amount of water and treated with 2 ml of 10 per cent trichloroacetic acid, and the mixture well shaken. After 10 minutes 3 ml of water were added, and the mixture was filtered. From the filtrate 4 ml were transferred to a 25 ml volumetric test tube. Water was added, followed by 1.5 ml of 12.5-N sulphuric acid and 2 ml of 5 per cent ammonium molybdate solution and water to the 25 ml mark. Then 0.5 ml of the reducing agent was added and mixed by inverting and shaking. The reducing agent was 0.25 per cent 1 : 2 : 4-aminonaphtholsulphonic acid in 14.5 per cent sodium meta-bisulphite and 0.5 per cent sodium sulphite, and was freshly made for each period of analysis. The colour of the test was compared after 15—40 minutes with a control solution without plasma in a photoelectric colorimeter, using red light filter (S 72).

Standardization of the readings was performed at short intervals by a dilution series of a standard phosphate solution. The calibration factor obtained from the series was further checked daily by measuring 4 or more specimens of a standard phosphate solution of 5 mg %, treated in the same manner as the plasma samples.

The *error of the estimation* of both plasma and standard solutions, computed as the standard deviation of 20 separate determinations of the same blood sample and from a large number of double determinations of standard solutions, was found to be 0.13 mg %, or 2.5 per cent of the mean value.

The Phosphatase Methods. During the series 2—4 (March—Oct. 1946) the method of Lundsteen and Vermehren was employed (see Vermehren,

1938), with some modifications. By this method the phosphatase activity is estimated by the amount of inorganic phosphorus liberated from an alkaline-buffered solution of sodium beta-glycerophosphate, used as substrate for the phosphatase. Unfortunately it was impossible to procure this substrate for the last two series of analyses. Then, the method of KING and ARMSTRONG, in the modification of BUCH and BUCH (1939), was employed. The substrate for the phosphatase is here phenol phosphate, and the liberation of phenol is determined by use of the phenol reagent of FOLIN and CIOCALTEAU. The procedure employed was in accurate accordance with the description of BUCH and BUCH (1939).

The *method of* LUNDSTEEN and VERMEHREN was applied in the following manner. 0.1 or 0.2 ml of the heparin plasma was diluted with 8 ml of 0.9 per cent sodium chloride solution. After shaking, 2 ml of the diluted plasma were transferred to 2 ml of the buffered glycerophosphate solution, made in accordance with the description given by VERMEHREN (1938). The tubes were thoroughly shaken and stoppered and kept in a water-bath at 37° C for 24 hours. Double determinations were usually made of each sample. The hydrolysis was stopped after the 24 hours by adding 4 ml of 10 per cent trichloroacetic acid to each tube. After 10 minutes the tubes were centrifuged or filtered, and 7 ml of the clear filtrate was taken for phosphorus analysis according to the method previously described. The readings were compared with control solutions without plasma, treated in the same manner as the tests. In this way the amount of phosphorus in the test volume was measured, and the corresponding amount of phosphorus in mg per 100 ml of plasma was calculated. From this value the content of inorganic phosphorus of the plasma itself was subtracted (about 4 mg per 100 ml). The rest is then the amount of phosphorus hydrolysed per 100 ml of plasma, and is called the number of "phosphatase units". For children the values were in the range 100—200 "units", and for adults about 50 "units", which is in agreement with the normal values given by VERMEHREN (1938).

In the *experimental control* of the method it was demonstrated, that the rate of the hydrolysis was constant during the 24 hours incubation period. It was also shown, that the phosphatase analysis of heparin plasma did not give significant differences from the values found by using serum.

The *error of the method*, calculated from the large number of double determinations carried out, was 10 "units", or 7 % of the mean. In a mean value of 20 single determinations on different individuals, the error due to the method is then only about $\pm$ 2 units.

The *phenolphosphate method* in the modification of BUCH and BUCH includes phenol determinations of the test solution and of a control solution of the same blood sample, where the enzyme has not had time to assert an action. The difference between these values permits the calculation of the number of "phenol units" per 100 ml of plasma or serum. It was found that the standard deviation of a single reading in this method was also $\pm$ 7 per cent of the mean for both the test and control solutions. It was also found, that the control readings did not differ significantly between different (healthy) individuals. Then, by using for the subtraction the average of the large number of control readings, in-

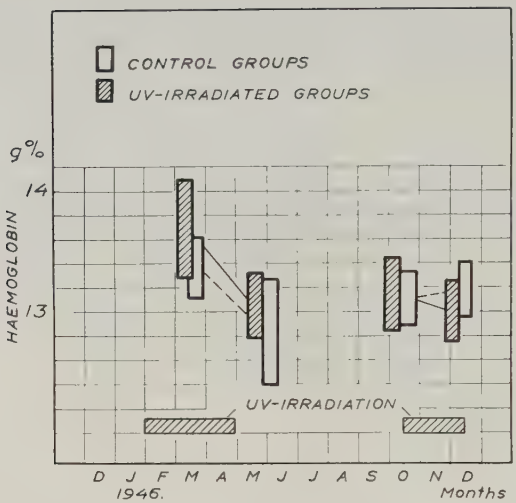

Fig. 30. Haemoglobin levels in irradiated and control groups of Primary school classes.[1]

stead of the individual control readings the error of a single determination could be practically maintained at $\pm$ 7 per cent.

This method was used only to detect any differences between the groups in each series. The values found are therefore given only as percentages of the (non-irradiated) control groups, and are unrelated for the two time-series,where the method was employed, and also for the values of the previous method.

Results.

The results obtained for the variations of the blood constituents analysed are given in the diagrams of figs 30—38.[1] As discussed above (p. 108), a statistically significant difference between two means obtained for different groups (i. e., uncorrelated samples) is indicated when the corresponding rectangles in the diagrams are mutually displaced so that a free space appears between them. A seasonal variation for one and the same group requires in general a smaller displacement of the rectangles to give the same degree of significance. The exact evaluation of this must be made with consideration to the correlation between the samples.

[1] In the following diagrams the heights of the rectangles denote the range of variation within which the *real* mean value of the group is to be situated with an evaluated probability of 90 per cent (see p. 108). The width gives an estimate of the number of observations in each group (usually about 25, see Table 9, p. 110).

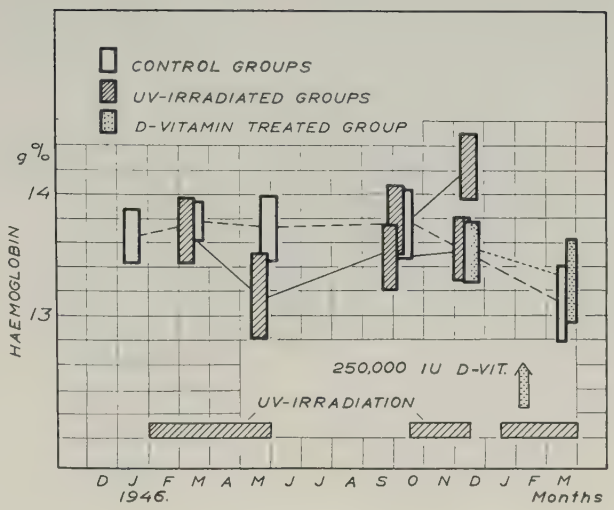

Fig. 31. Haemoglobin levels in experimental and control groups of Secondary school classes.

For the first period, December 1945—May 1946, the control group (i. e., open rectangles in the diagrams) of the Secondary school children has been made up of Group II and the boys of Group III, thus consisting of only boys in conformity with the experimental Group I (see fig. 29, p. 105). The girls of Group III during this period were not included in the statistical treatment. From the following term (Sept. 1946) Groups I—III consisted only of boys aged 10—11 years.

The experimental Group IV of the Primary school children with the corresponding control Group V consisted of both boys and girls, aged about 7 years, during the whole investigation, and the statistical treatment has been made on the combined material.

Effect on Haemoglobin Concentration.

The variations of the haemoglobin concentration of the blood found in the different groups during the investigation are summed up in diagrams, figs 30 and 31, for the Primary school children and the Secondary school children, respectively. In the main there are no differences between the mean values of the irradiated and non-irradiated groups, in spite of the former showing some small deviations in some of the series. These differences cannot, however, be given much significance, due to the lack of uniformity in the response,

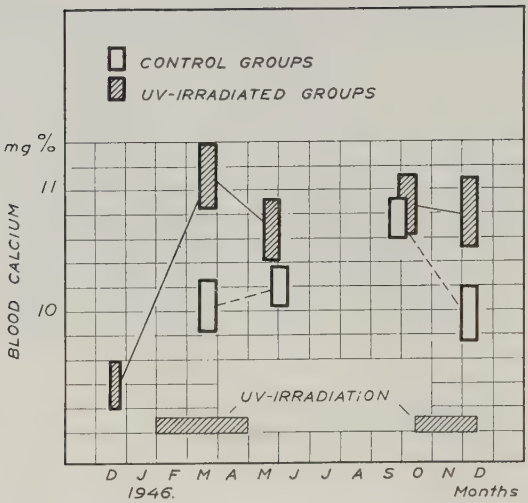

Fig. 32. Plasma levels of total calcium in irradiated and control groups of Primary school classes.

also within the same time-series of estimations.[1] The findings thus indicate that *a continuous low-intensity ultraviolet irradiation of healthy children during the winter does not exert a significant influence on the haemoglobin concentration of the blood.*

That the presence of ultraviolet radiation is not an essential factor for the maintenance of the haemoglobin level in the blood is further supported by the *absence of a uniform seasonal variation* of the haemoglobin concentration in this material. If the ultraviolet radiation were a specific factor for the formation and the maintenance of the haemoglobin content of the blood it would be expected that the values of the control groups would decrease during the course of the winter and increase during the summer. This is not indicated by the present material.

The administration of a massive dose of vitamin D to the non-irradiated children of Group III (fig. 31) did not significantly affect the haemoglobin level (see p. 121).

The failure of an effect of the ultraviolet irradiation on the haemoglobin content of the blood of these healthy school children agrees

[1] The comparatively high mean values found in the Primary school groups in the analysis of March 1946 (fig. 30) may be due to a systematic error in the estimation. The visual photometer readings were in this case performed by another person than in the later series.

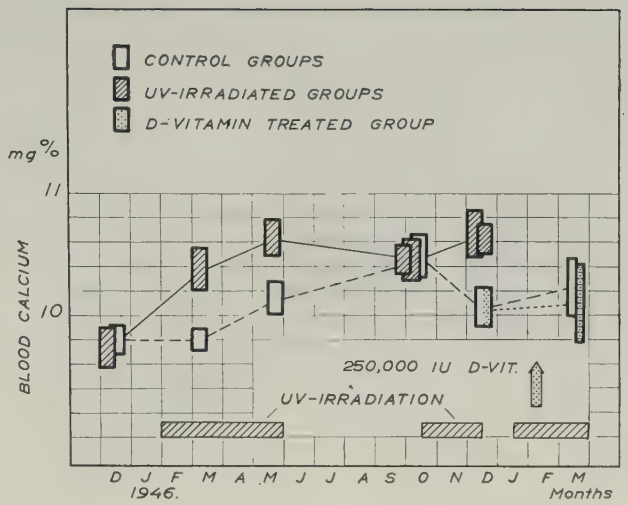

Fig. 33. Plasma levels of total calcium in experimental and control groups of Secondary school classes.

with the now generally accepted view that radiation may be a secondary, additional factor for the restoration of the haemoglobin concentration and the red blood cell count of the blood in cases of secondary anaemia, *the primary factor for the maintenance of normal values, however, always being adequate nutrition* (Laurens, 1933, 1938; Mayerson, 1935; Handbook of Physical Medicine, 1945, p. 285). The conception previously prevalent regarding the darkness of the winter as the cause of a seasonal variation of the haemoglobin content of the blood in infants, with a minimum concentration in spring, is now in the main replaced by the view that this possible variation depends upon the increased frequency of infections during the winter (Barenberg, Friedman, and Green, 1926; Faxén, 1937; see also p. 31). Vitamin D deficiency does not itself cause anaemia, and anaemia combined with rickets is not cured by antirachitic treatment (Bauman, 1928, cit. Mayerson, 1935; see also Schönfeld, 1939).

Effects on Calcium and Phosphorus Metabolism.

The plasma level of calcium.

From figs 32—33 it is apparent that the ultraviolet irradiation caused a *marked increase of the calcium level* of the plasma, significantly

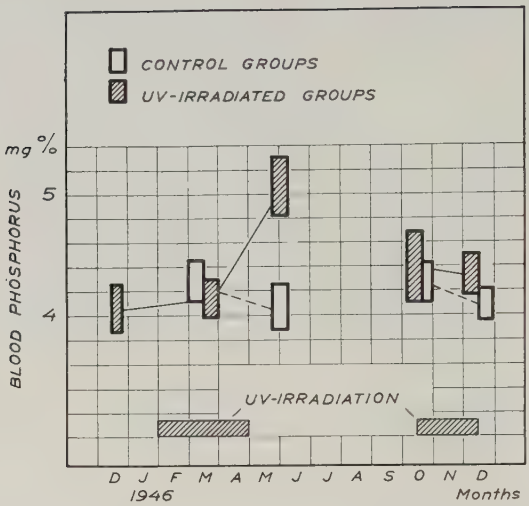

Fig. 34. Plasma levels of inorganic phosphorus in irradiated and control groups of Primary school classes.

occuring in all the irradiated groups during the winter months. The elevation was especially marked in the irradiated Primary school class (Group IV) during the first term, when the ultraviolet intensity in the illumination was highest.

It is also clearly demonstrated that the untreated control children exhibit a *uniform seasonal variation* of the plasma calcium level, with the maximum values in the autumn and the minimum values in the late winter months. The amplitude of the variation seems to be somewhat larger in the groups of the younger children. *By means of the UV-illumination system employed in the classrooms this seasonal variation is cancelled, with the calcium concentrations maintained at the height of the normal autumn level.*

Single values as high as about 12.5 mg % were found in some of the irradiated groups during the winter and in all groups at the autumn analysis. There is no reason to assume that the calcium levels reached by the artificial irradiation fall above the normal upper limit of it. The standard deviation (σ) of the samples varied between 0.3 and 0.6 mg % in both the irradiated and control groups, and with an average of about 11 mg %, as found in the autumn analysis, single values should be expected to reach the range about $(11 + 3 \cdot \sigma)$ mg %, i. e., about 12.5 mg %, due to the random distribution.

In the groups containing children of both sexes it was noticed in 9 out of 11 such samples that the calcium concentrations of the plasma were higher among

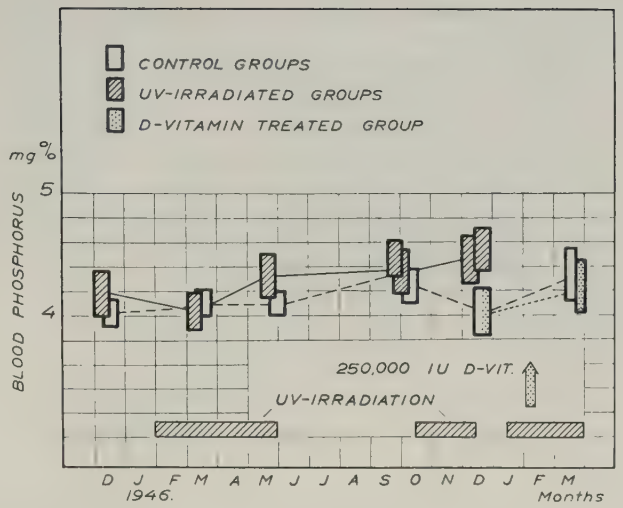

Fig. 35. Plasma levels of inorganic phosphorus in experimental and control groups of Secondary school classes.

the girls. The difference was statistically significant in some of the series, but the mean difference between girls and boys during the whole period of the investigation was only 0.2 mg %.

The plasma level of inorganic phosphorus.

The variations of the plasma concentration of inorganic phosphorus is seen from figs 34 and 35 for the groups of Primary and Secondary school children, respectively. The effect of the irradiation was not at all so pronounced as for the calcium concentration, but *some increasing effect during the winter months seems probable.* The significance of the difference found between the combined irradiated Groups I and II and the control Group III in the analysis of December 1946 (fig. 35) corresponds to a probability of about 0.01. The comparatively very high mean value obtained in May 1946 in the irradiated Group IV (fig. 34) was checked by double determinations on about half of the same children, after an interval of one week. It should be pointed out that this sudden increase of the phosphate level occured *after* the irradiation had been removed for about one month.

It is also seen from the figures that the results *do not indicate any pronounced seasonal variation* of the plasma inorganic phosphate concentration in this material. As for the haemoglobin variations

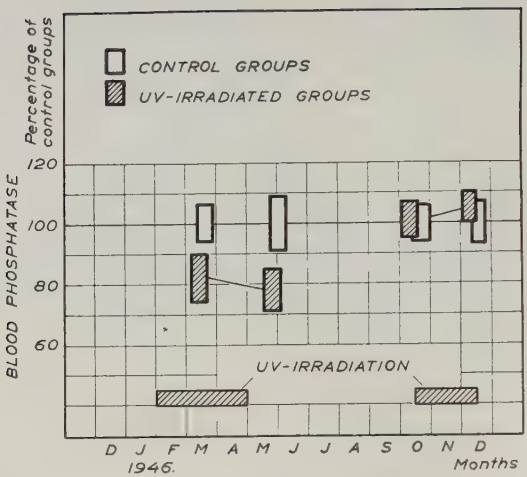

Fig. 36. The relative levels of the plasma activity of alkaline phosphatase in irradiated groups compared with control groups in the Primary school classes.

the failure of a marked effect of the artificial irradiation during the winter in combination with the absence of a seasonal variation may be taken as evidence that ultraviolet energy is not the main factor influencing this blood level in children of school age.

The phosphatase activity of the plasma.

In figs 36 and 37 for the Primary and Secondary school children, respectively, the 90 per cent probability range of the means of the non-irradiated control groups have been plotted around a relative value of 100 in all the series of determinations, and the means of the experimental groups are expressed as the percentages of the corresponding control group. It is seen that in most of the series of analyses carried out during the winter and spring months there was a *significant decrease of the alkaline phosphatase activity in the blood of the irradiated children.*

A measure of the *seasonal variation* of the phosphatase activity was, for methodical reasons, only obtainable during the period March—October 1946, including three series of estimations. The only children followed consistently over this period were those of Groups I and II, and the values found for them by the method of Lundsteen and Vermehren are summed up in fig. 38. The marked decrease of the

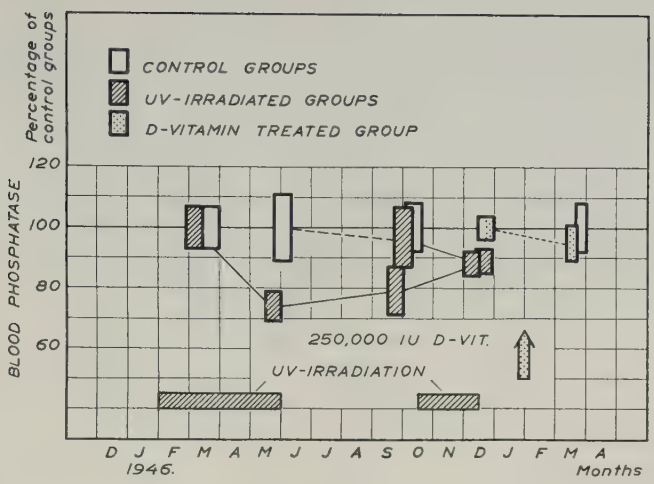

Fig. 37. The relative levels of the plasma activity of alkaline phosphatase in experimental groups compared with control groups in the Secondary school classes.

blood phosphatase activity normally occurring during the summer season is demonstrated, and it seems reasonable to assume that *the low summer value can be maintained by the continuous ultraviolet irradiation during the winter.*

The Vitamin D Experiment.

In order to study if the blood effects observed with the children of the UV-illuminated groups during the winter could be obtained simply by a *supplementary administration per os of vitamin D*, the following preliminary trial was made.

For several reasons, however, it was not possible to organize this trial on a scale sufficient to be expected to yield significant and reliable results. The only possibility left was to give a massive dose of pure vitamin D to a limited number of the control children at mid-winter and study the effects of this. A better treatment of the question would obviously have been to provide for a continuous and sufficient supply of vitamin D during the whole winter, and to use a material sufficiently large to permit general conclusions. The intentions of this trial are only indicative.

At the beginning of the spring term 1947 (Jan.—Feb.) a dose of 250,000 I. U. of vitamin D_2 (calciferol in oil; "Ultranol fortior", containing 250,000 I. U. per ml) was given to every second boy of the

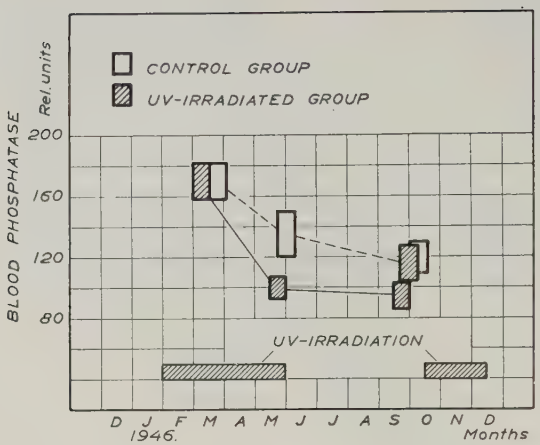

Fig. 38. Seasonal course of the plasma activity of alkaline phosphatase in the Secondary school classes for the summer half-year.

control Group III (aged about 11 years). The vitamin was administered *per os*, mixed in a small amount of milk, and divided into two equal parts given with an interval of two weeks. The other boys of the class were given at the same times some paraffin oil in the milk, unconscious of the difference. After about one month new blood samples were taken and analysed as before with regard to the concentration of calcium, inorganic phosphorus, alkaline phosphatase and haemoglobin. The results obtained are shown by the pointed rectangles in the previous diagrams. It is seen that there was *no significant effect of the vitamin D administered in any of these respects.*

With regard to the small sample studied and to the manner of administration employed it would, however, be wise to postpone any decisive statement on this question until further experiments are carried out, with larger samples and with a continuous administration of the vitamin during the winter. The failure of an effect on the blood constituents should be compared with the effect obtained on physical fitness (p. 144).

Discussion.

It is shown that the calcium and phosphorus metabolism, as reflected primarily by the plasma concentrations of total calcium and alkaline phosphatase, is subject to a *seasonal variation* in Swedish

school children of 7—10 years of age with a presumed adequate diet. The *plasma level of calcium* showed a decrease during the course of the winter with the minimum values reached about March, and an increase during the summer to a maximum value in September or October. The activity of the *alkaline phosphatase* in the blood varied according to a seasonal curve which is the inverse of that for the calcium level, i. e., with the maximum value in spring and the minimum value in autumn. The level of *inorganic phosphorus* in the plasma remained almost unchanged during the course of the year, and the same was the case with the haemoglobin level.

The variations of the calcium and phosphatase levels in the blood were completely *counterbalanced by a continuous low-intensity ultraviolet irradiation* of the children during the winter, applied by means of the UV-illumination system in the classrooms. The values were maintained at the normal autumn levels, which may be regarded as constituting the optimal condition for the calcification of the growing bones. There was also some increasing effect of the irradiation on the plasma concentration of inorganic phosphate, but this was not so marked as for the calcium and phosphatase concentrations. Thus, *the effects of the artificial irradiation during the winter were first seen with those functions which otherwise exhibit a marked seasonal variation.*

It seems reasonable to assume that these effects of the UV-illumination system are due, in the first place, to a *photochemical formation of vitamin D and related substances in the skin of the irradiated children.* The mechanism of the vitamin D action on the human body is, among other things, to increase the net absorption of calcium from the intestine (Nicolaysen, 1937; Greenberg, 1939, 1945), while the effect on the phosphorus absorption is less pronounced (Cohn and Greenberg, 1939). An early symptom of vitamin D deficiency in infants is the increase of the activity of alkaline phosphatase in the blood, and the elevated phosphatase values are brought back to the normal values by administration of vitamin D (see Folley and Kay, 1936.)

The vitamin D experiment carried out in this investigation, with the administration of a massive dose of calciferol (250,000 I. U.) to non-irradiated children in mid-winter did not, however, reproduce the irradiation effects on the calcium, phosphorus and phosphatase levels in the blood. With regard to the small sample treated and the mode of administration of the vitamin too much significance cannot, however, be attached to this isolated result.

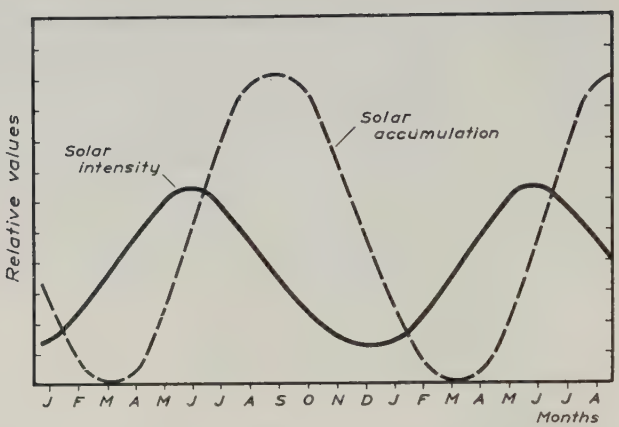

Fig. 39. Theoretically deduced variation of the accumulation in the body of solar-formed substances in relation to the variation of the solar intensity. (After HORSTMANN and PETERSEN, 1946).

The seasonal variation recorded for the calcium and phosphorus metabolism follows the annual course expected for the influence of such a substance as vitamin D, which is mainly supplied to the body by the solar ultraviolet radiation and is balanced in the body metabolism over the year. The accumulation of such a substance in the body should increase during the time of the year when the formation is greater than the consumption, that is, during the summer half year, and the maximum storage in the body should be expected around the autumn equinox (23. September in the northern hemisphere) and the minimum storage around the spring equinox (21. March). The annual course of the incidence of rickets and spasmophilia in infants in Denmark is recently shown by HORSTMANN and PETERSEN (1946) on a large material to follow closely such a theoretically deduced annual curve of the vitamin D accumulation in the body (see fig. 39). It is presumed that the rate of consumption is constant over the year and that the amount of the vitamin consumed in the year equals the amount formed by the solar radiation.

The seasonal variation actually recorded for the calcium and phosphorus metabolism of the children thus gives evidence for the fact that *the reduction of the solar radiation during the winter was not sufficiently replaced by the normal winter-diet alone to maintain the optimal condition found in summer and autumn,* and the important role played by the ultraviolet radiation is directly proved by the UV-

illumination effects. The autumn levels of calcium, phosphorus and phosphatase in the blood may be regarded as optimal, since they are farthest away from the conditions characterizing rickets (cf. SHOHL, 1939).

HEYMANN (1937) found that after a single massive dose of vitamin D the liver and the blood plasma of rabbits maintained antirachitic properties for 8—12 weeks, and WARKANY, GUEST, and GRABILL (1942) have reported that dried powder of human blood serum is antirachitic for three to six months after the administration of 500,000 I. U. of vitamin D. These findings indicate that the storage of vitamin D in the body from the summer sunshine must be considerably reduced during the course of the winter if no other sources of the vitamin supply are present during this season. The very low intensities of antirachitic ultraviolet radiation prevalent in the natural outdoor daylight during the winter at the latitudes of Scandinavia is mentioned previously, and the limited supply of vitamin D by normal foodstuffs is wellknown (see BICKNELL and PRESCOTT, 1946, p. 652). It is obvious that there really exists a latent risk of vitamin D deficiency in humans during the late winter months.

Previous investigations on seasonal variations of the blood content of calcium, inorganic phosphorus and alkaline phosphatase have only been made on babies, i. e., at the age of the infant when it is susceptible to the roentgenological manifestations of vitamin D deficiency. BAKWIN and BAKWIN (1927) reported such a seasonal variation of the calcium concentration of infant's serum from 8.5 mg % in February—March to about 11 mg % in August—September. HESS and LUNDAGEN (1922) and BRUUN (1927) have described a similar annual course for the plasma concentration of inorganic phosphate in infants about twelve months old, and VERMEHREN (1938) found a marked decrease of the phosphatase activity in the blood of small infants during the summer. These variations are ascribed by all the authors to the variation of the vitamin D supply due to the seasonal variation of the intensity and duration of the solar ultraviolet radiation.

The question, however, arises whether all the effects of ultraviolet irradiation on the calcium and phosphorus metabolism are due solely to an increased supply of vitamin D, or if there is also a *hypercalcaemic*, "*calcinosis*" *effect* involved. This would mean that at least part of the rise of the calcium level in the plasma is due to a dissolution of calcium compounds from the bones instead of, or combined with an increased absorption from the intestine. Such a calcinosis effect of ultraviolet radiation, due to the formation in the skin of a substance related to A. T. 10 of HOLTZ, has recently been assumed by BROCKMÜLLER (1940) and PFEIFFER (1942).

An early blood-chemical symptom of a vitamin D deficiency in infants is usually a fall of the concentration of inorganic phosphate in plasma or serum, besides an increased activity of phosphatase, while a drop of the calcium con-

centration occurs first in later stages (see, e. g., Rominger, 1939; Clements, 1946). The most marked effect both of the artificial and natural ultraviolet irradiation of the children was in this investigation found on the calcium level, and the least effect on the inorganic phosphate level. However, the metabolic effects of vitamin D deficiency in older infants, as involved in this investigation, are not so wellknown; the hypophosphataemia is said to be less pronounced than in the common form of rickets, connected with the normally occurring decrease of the phosphate level in blood with age (Schönfeld, 1939). In adults, ultraviolet irradiation during the winter is found by Pontén (1939) to cause an increase of the serum calcium concentration to the normal autumn value of 10.5 mg per 100 ml, but without significant effect on the inorganic phosphate concentration. Brockmüller (1940) found a rise of serum calcium of about 0.5 mg per 100 ml after ultraviolet irradiation ("Höhensonne") of 17 normal adults, and ascribes this effect, as mentioned above, to a photochemical formation in the skin of a calcinosis factor related to dihydrotachysterol (A. T. 10, see Holtz, 1934, 1939). The increase was somewhat higher in winter. Pfeiffer (1942) reported the same findings, based on a material of 33 normal adults, and agrees with the theory of Brockmüller. The effect on the inorganic phosphate in the serum was not studied in either of these investigations. The serum calcium increasing effect of ultraviolet irradiation was noted already by Rothman in 1923.

Among the intermediate products in the photochemical conversion of provitamin D to vitamin D, at least tachysterol is known to have a calcinosis effect, which, however, is only 1/10 of that of A. T. 10 (see Rosenberg, 1945). The antirachitic effect of these compounds is very small. The amount of A. T. 10 needed to raise the serum calcium concentration is as high as 2 mg per day, while the amount of calciferol, or vitamin D_3, which prevents or cures rickets is only about 25 μg per day (= 1,000 I. U.; see Cohn, Cohn, and Aub, 1942). It is evident that some part of the provitamin D present in the skin during ultraviolet irradiation remains at the tachysterol stage, and may be converted into more active forms, but it seems doubtful that the irradiation of a small skin area can leave amounts of tachysterol sufficient to give an increase of the serum calcium in this way. Irradiated ergosterol preparations (viosterol) contain about 50 per cent calciferol (vitamin D_2), the antirachitic principle, and some of the remainder is tachysterol (McLean, 1941). In a study of adolescent healthy monkeys (Macacus rhesus) for the effect of small doses of a concentrated preparation of viosterol, Cowdry and Scott (1936) did not find evidence for the calcium level being significantly affected, but a marked rise of the phosphorus concentration was apparent. The doses of the viosterol preparation used were in all cases far in excess of what might be expected to be therapeutic for the monkeys in question.

Over-irradiation of vitamin D results in the formation of toxisterol (substance 248), which is known to cause hypercalcaemia and metastatic calcifications when given in toxic doses. Direct irradiation of the skin with ultraviolet is, however, said never to cause such toxic

symptoms (Holtz and v. Brand, 1932; Dodds, Robertson, and Roche, 1934). Rosenberg (1945) writes: "The deleterious effect observed on the normal organism upon over-irradiation is independent of vitaminization. This suggests that a special protective mechanism exists in the body, probably in the skin, which takes care of the potential effects of an over-irradiation of the provitamin D."

The material of this investigation does not permit a causal interpretation of the changes recorded for the calcium level, as this presumes an exact study of food and excretion, retention and balance of the calcium and phosphorus compounds. It does not seem, however, justified to regard the effects of the ultraviolet irradiation on the calcium level as toxic, but, on the other hand, the possibility can not be excluded that this irradiation effect involves further mechanisms than just the formation of vitamin D. A possible bone-dissolution effect of ultraviolet irradiation could be appropriately studied by means of the radioactive isotopes of calcium and phosphorus, used by Greenberg and Cohn in the studies of the mode of action of vitamin D (Cohn and Greenberg, 1939; Greenberg, 1945).

CHAPTER 11.

Effect on Physical Fitness of the Children.

Based upon the reports of Lehmann and Szakall (1932 a–b, 1944) on the improving effect of ultraviolet irradiation of man upon the capacity and efficiency for performing physical exercise, which in different ways have been supported by, among others, Moschkowsky (1936), Parade and Otto (1939) and Allen and Cureton (1945), it was decided to study the UV-illumination system regarding this effect also. The inherent difficulties in obtaining valid and reliable information on the fitness for physical exertion of children were clearly realized, but the problem was simplified as the main purpose of the study was to look for possible *variations of the physical fitness of the same individuals* during the time of the investigation.

The important choice of the *method of test* was influenced by the desirability of testing large samples of children in short intervals and without too much interference with the school timetable. Any test

of the maximal physical performance (until exhaustion) was considered unsuitable for application to this child-material, as all such tests are influenced too much by the subjective motivation of the individual to give valid and reliable information, and they also involve some elements of risk. The method finally employed was *a set of cardiovascular tests applied during a continuously graded work on a bicycle ergometer*. In the main the procedure employed is based on the method described by LEHMANN and MICHAELIS (1941). The cardiovascular measurements, which were made during the working period, involved determinations of blood pressure and pulse rate, and the following *criteria of fitness* were used:

1. the total amount of work (in kilogram-meters, kg. m) performed until the product of pulse rate and pulse pressure reached the numerical value 10,000 (LEHMANN and MICHAELIS),
2. the pulse rate at 5 minutes after the beginning of the work, when the amount performed was just 1,000 kg. m, and
3. the pulse pressure after 5 minutes.

In different ways these criteria give an estimation of the stress caused by a moderate muscular work on the cardiovascular system of the subject. A large amount of work performed until the product of pulse rate and pulse pressure equals 10,000, and, consequently, low values of the pulse rate and pulse pressure after a moderate standard amount of work, indirectly indicate a high, latent capacity for heavy work, at least in normal healthy humans. The actual values of the fitness-indices obtained by these tests on a population depend, partly, on the muscle mass of the subject and, partly, on the general working efficiency of the body. Significant variations of the fitness of the same individual during short intervals of tests, without involving any special physical training, must, however, be primarily due to a change in the *efficiency of the muscular and cardiovascular system to withstand the stress caused by a sub-maximal physical exercise*. A detailed account and discussion of the method employed is given below.

It was found that in the homogeneous samples of the school classes involved in this study the values of fitness obtained by these methods were distributed in close agreement with the normal random distribution curve. The material has then been treated in accordance with usual statistical methods of normal random samples. The mean values of the groups are evaluated by the *t*-test and reproduced in diagrams as

Table 10. *Scheme of Tests on Physical Fitness. Only Boys.*

Time	Group I	Group II	Group III
Jan.—Feb. 1946	26	23	—
April 1946	21	20	—
May 1946.....	20	24	—
Sept. 1946	21	23	23
Dec. 1946.....	20	23	23
March 1947	—	17	28[1]

[1] 14 of whom had received vitamin D.

rectangles showing the 90 per cent probability range of the real mean, as was also employed for the results of the blood analyses (see p. 108). It should be noted that the significance of possible differences between two means of the same group on different occasions (seasons) must be evaluated with respect also to the correlation between the samples; the displacement of the rectangles decidedly under-estimate such a significance and may not be used for an estimate of it.

Only the boys of the Secondary school classes (Groups I—III, see fig. 29, p. 105), aged 10—11 years, have been subjects of the investigation. The time scheme and the number of individuals in the six series of tests carried out is shown in Table 10.

The Test Methods Employed.

The Physiological Basis.

The problems concerning measurement and evaluation of fitness for physical exercise have been particularly treated during the years of the recent war, and some of the prominent works carried out are reviewed by Simonsson (1944), H. L. Taylor and Brozek (1944), C. Taylor (1945), and Karpowich (1947). Only some orientating notes will be given here, mainly referring to the specific questions of the present investigation.

The internal human factors influencing *the maximal amount of physical work an individual can perform* in a given situation, as in repeated, constant laboratory tests on his "fitness", may be schematically divided into the following groups:

1. the actual *mass of muscles* available for the work (the morphological factor),
2. the *power and effectiveness* of the muscle contractions (involving a metabolic, biochemical factor),
3. the degree of optimal *innervation and coordination* of the muscles (the central nervous factor),
4. the power of adaptation of the *respiratory* and *cardiovascular systems* to the increased demand of oxygen (the oxygen-supply factor), and
5. the *psychological factors.*

All these factors may vary considerably between different individuals, thus giving their real, but difficult to estimate grading with respect to the absolute working capacity. *The only defensible a priori criterion of the fitness of a man for heavy physical exercise is,* as C. Taylor (1944) states, *the amount of such work the man can do until exhaustion.* This limit is, however, always a subjective one, and is decisively influenced by the optimal motivation and interest of the subject. Tests based on this criterion require an intelligent cooperation of the subject if reliable estimations should be obtained. It is obvious that such maximal performance tests are applicable mainly in laboratory investigations on selected material and not suited for a field-investigation like the present one on school children.

The way most commonly used for the estimation of physical fitness is, therefore, the application of *sub-maximal performance tests.* In these the response of some physiological factors to moderate physical work is measured and used as an indication of the latent capacity for heavier work. The criteria commonly used in such tests are cardiovascular in origin (as in, for instance, the Schneider test), but others have also been employed, as the blood concentration of lactic acid after the work, the respiratory exchange and the pulmonary ventilation, etc. *The reliability of all such submaximal criteria must be controlled with respect to the correlation they offer to the real maximal performance.* C. Taylor (1944) found in such a study that the most useful and reliable single criterion in sub-maximal tests on working capacity is formed by the *pulse rate after a standard, moderate amount of work.* The correlation found between the pulse rate during walking on a tread-mill and the time-run to exhaustion was — 0.56, while multiple correlation of pulse-rate, pulmonary ventilation in liters/min., and blood lactate concentration in the sub-maximal phase of the test only gave the slightly better value of 0.63. By using special heart-rate curve functions a correlation of 0.90 could be obtained. In maximal work tests, on the other hand, the increase of pulmonary ventilation and related functions is the most reliable objective index of approaching exhaustion (C. Taylor, 1942).

When a variation of a cardiovascular criterion is observed on the same subject during the course of repeated tests, and the influence of psychological and environmental factors as well as any significant growth of the muscles can be excluded, the primary reason must be looked for in a variation of either the *motor efficiency* or the *cardiovascular response,* or both. The motor efficiency may be expressed by the *mechanical efficiency coefficient,* i. e., the quotient of the

work output to the total heat production. It is influenced mainly by factors 2. and 3. in the scheme above, i. e., the effectiveness of the muscle contraction and the degree of coordination of the muscles used. The latter may be the main factor influenced by physical training, but the activity and speed of the metabolic processes and the oxidation mechanisms may also be of importance (cf. Wiggers, 1944, p. 914). The total heat production is a function of the oxygen intake, and thus an improvement of the mechanical efficiency of the muscles is reflected in the cardiovascular system, as the demand of oxygen intake for a given amount of work is decreased. It was shown by Collet and Liljestrand (1924 b) that training causes a decrease of the minute volume of the heart for a given kind and amount of work, and the sense of effort involved in the work was apparently correlated to the minute volume. Christensen (1931) also found higher values of the minute volume during work in completely untrained persons. The findings of Christensen do not, however, indicate that the main effect of physical training is a decrease in the minute volume for the same amount of work. In most of the subjects the minute volume was about the same for the given work output, but there was a marked decrease of the pulse rate in the most trained individuals. The conclusion is that physical training also exerts a direct influence on the heart, causing it to enlarge and thus increase the cardiac output (cf. Christensen, 1937). Observations on effects of training on pulse rate and blood pressure, carried out by Cogswell et al. (1946), showed a decrease of post-exercise pulse rate after submaximal exercise, while maximal tests failed to produce a similar response. Systolic blood pressure, resting and post exercise, tended to decrease with training.

This schematic interpretation is intended to show that a record of variations of some cardiovascular criteria during the course of repeated series of work tests does not permit conclusions regarding the cause of the variations. This may be muscle-metabolic, nervous, or circulatory in origin, or combinations of these. In the main, however, *low values of both minute volume, pulse rate and blood pressure after a moderate amount of work may be used as indicators of a good physical condition of a subject*, permitting him to perform physical work with greater efficiency and smaller effort.

The sub-maximal fitness test introduced by Lehmann and Michaelis (1941), which has formed the basis for the procedure applied in the present investigation, differs somewhat from other sub-maximal tests described. The latter usually involve the measurement of the response of some physiological factor of importance for the working efficiency of the body after a standard amount of work and the response is used as the criterion of the fitness. The criterion in the method of Lehmann and Michaelis is, on the other hand, formed by the amount of continuously graded work necessary to give a certain value of the response. The response used is the product of pulse rate and pulse pressure, which is taken as a rough estimation of the minute volume of the heart, and the working time until this product exceeds the numerical value of 10,000 is the criterion applied.

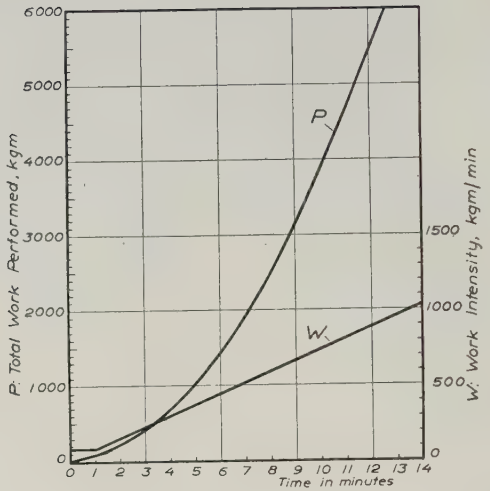

Fig. 40. The grading of the work (work intensity) and the total work performed at different times during the ergometer test.

The reliability of this product for the estimation of the minute volume was first studied by Liljestrand and Zander (1928). It was found to be an approximately constant relation for the same individual in work tests, the product however rising more and also faster than the minute volume. A somewhat better correlation was found by using the "reduced" pulse pressure, i.e., the percentage of the pulse pressure to the mean blood pressure (see also Apéria, 1942). If, therefore, the product used by Lehmann and Michaelis only gives an approximate estimation of the minute volume, the criterion involves the advantage to fitness-tests of also including the pulse-rate function. The latter may of course also be treated separately as a fitness-criterion.

According to the description of Lehmann and Michaelis the test person should work on an ergometer bicycle with the work load continuously increasing at a constant rate. The initial output is adjusted so that the work intensity per square centimeter of the calf cross-section is similar for all the persons. The time until the product of pulse rate and pulse pressure reaches the numerical value 10,000 is the measure taken of the fitness. It is claimed that in this way the method gives a reliable grading of different individuals according to their fitness for physical work.

The main purpose of the work tests carried out during the present investigation was to follow the development of the physical fitness of the same individuals in a rather homogenous sample, without intending to obtain a grading of the different individuals. Because of that no differentiation has been made of the initial load intensity, so that the test has been exactly similar for all the children and in all of the series of tests carried out.

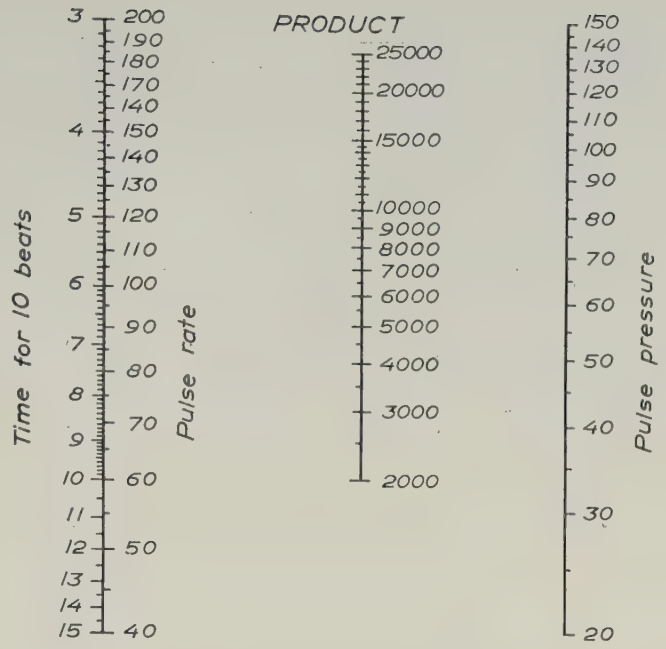

Fig. 41. Nomogram for calculating the product of pulse rate (beats/min.) and pulse pressure (mm of Hg).

The Procedure.

An electrodynamic brake bicycle ergometer, according to the original model of Krogh (1913), was used. The pedalling rate, indicated by a metronome, was fixed at 50 revs/min. There was usually no difficulty for the children to learn to keep this rate. The work intensity during the first minute of the test was kept constant at the small value of 90 kg. m/min. Then by a special arrangement a small steel ball of 16 g was made to drop on the balance of the ergometer every 4th second, causing an increase of the work intensity corresponding to 72 kg. m/min². The work intensity (A), in kg. m/min., after t minutes from the beginning of the load increase, i. e., $(t + 1)$ minutes from the start of the test, is then expressed by the relation

$$A = 90 + 72\,t \tag{1}$$

The total work performed (P), in kg. m, after t minutes is obtained by the integral

$$P = \int_0^t A\,dt = 90 + 90\,t + 36\,t^2 \tag{2}$$

These relations are given as curves in fig. 40.

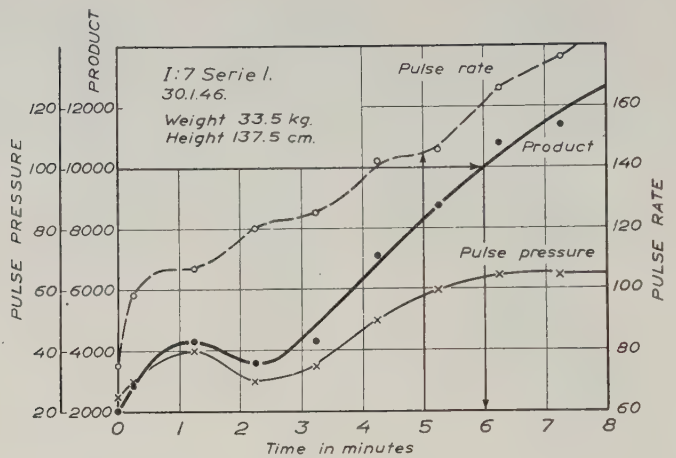

Fig. 42. A typical diagram plotted for a work test on the bicycle ergometer; such diagrams were plotted for each test carried out. — The initial peak occurring after 1–2 minutes is typical, showing the »warm-up» of the subject (cf. WIGGERS, 1945, p. 917).

During the work on the ergometer the blood pressure and the pulse rate were determined every minute. Afterwards, the pulse pressure, i. e., the difference between systolic and diastolic reading, was calculated, and the corresponding product of the pulse pressure and the pulse rate was quickly computed with the aid of the nomogram seen in fig. 41. The values obtained during every test were plotted in diagrams as shown in fig. 42. The time until the product of pulse rate and pulse pressure reached the value 10,000 was obtained by freehand interpolation in the diagram, and the value was converted into kilogram-meters of work performed by use of equation (2) given above. The pulse rate and the pulse pressure at 5 minutes from the start of the test ($P = 1{,}025$ kg. m) were also obtained in similar ways from the diagrams.

In some of the series carried out attempts were also made to obtain information of the *maximal performance* of the child. He had then to continue the work until he could no longer maintain the pedalling rate. The very subjective character of this "exhaustion" limit was apparent and could be clearly demonstrated by introducing simple encouragements and such like.

The *blood pressure determinations* were made auscultatory with the bell of a membrane stethoscope attached with an elastic bandage over the cubital fossa, below the armlet (width 12 cm). The tubes of the manometer and the pump of the armlet were drawn and fixed to a table besides the ergometer, where the operator had his place. The pressure readings were made with the arm hanging slack, when the armlet was at the heart level. In this way there were usually no difficulties in making exact readings during the first minutes of the work, when the load was still at low values, later becoming more difficult due to the muscle strain and shrugging of the child. However, in almost all cases the readings could be performed with sufficient accuracy until the required

sub-maximal criteria had been obtained. For the product criterion the time value varied for most of the cases between 5 and 8 minutes, while the time to exhaustion was usually 7—10 minutes. The pressure readings were usually corrected to the nearest 5. The diastolic pressure was read at the beginning of the last muffled phase of the disappearing sound ("the fourth phase of KOROTKOW"). The determinations of the pulse rate were made by counting 10 beats heard by auscultation with a supra-diastolic pressure applied.

The tests were always made in the morning between 8 and 11 a. m. and on about 10 boys daily. The temperature and humidity of the environment were always controlled and kept as constant as possible. The great importance of the psychological "atmosphere" during the test was well realized, and all sources of disturbances were eliminated. Great care was devoted to make the boys familiar with the method, and their initial nervousness was usually quickly lost. The tests soon become a kind of sport for the boys, which increased their interest and counteracted any fear of the test. A control of the emotional status was always made by frequent measurements of blood pressure and pulse rate before the start of the test, with the boy placed on the ergometer. All cases of apparent nervousness as well as any case complaining of discomfort or chill are of course excluded from the final treatment of the data.

In the first series of tests carried out (Jan. 1946) the girls of Group III were also included. It was, however, found considerably more difficult to obtain reliable estimations on them than on the boys, mainly due to their nervousness and fear of the test. As the irradiated groups did not contain girls, the following tests were made only on boys.

Undoubtedly it would have also been of value to follow the variations of the resting pulse rate and blood pressure values of the children. To get the true resting value, however, the resting period must be at least 20 minutes (cf. COLLET and LILJESTRAND, 1924 a) and this would have completely spoiled the time scheme of the investigation.

Experimental Control of the Method.

The control of the reliability and accuracy of the tests has consisted of the following studies.

The frequency distribution. When the first series of determinations were made in January 1946, comprising 46 boys and 11 girls, the results were expressed as the time in minutes until the product of pulse rate and pulse pressure had risen to 10,000 (the product criterion). The frequency distribution curves formed by the fitness-values in this unit were, however, rather skew in some of the groups. If the values, on the other hand, were expressed with the total amount of work performed until the criterion was reached as the unit, the distribution curves were usually in closer agreement with the normal distribution curve. The combined material with this unit for the first and the fourth series was tested by the χ-square method with respect to the deviation from the normal distribution curve (see KEMP, p. 112), and no significant deviation was

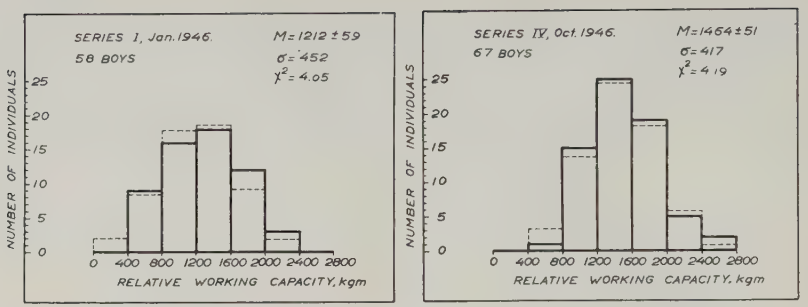

Fig. 43. The frequency distribution of scores of physical fitness obtained by the product criterion (full-line histogram). The dotted lines show the theoretically expected distribution.

estimable (fig. 43). The latter measure was then considered more suitable to use for comparisons between the different samples and series of determinations, as the material could be treated in an ordinary statistical manner.

A statistical analysis carried out at a later stage of the investigation showed, however, that neither did the frequency curve obtained with the time values as unit deviate significantly from the normal distribution curve. This simpler unit may thus be applied as well as the unit used in this investigation.

The pulse rate and the pulse pressure at 5 minutes from the beginning of the test (the pulse rate and the pulse pressure criterion, respectively) were also shown to be distributed in full accordance with the normal curve, thus permitting the usual statistical treatment of the data obtained.

The reliability of the estimations. Three or four tests were made on each of 11 boys *at different times of the same day*, with the results of the product criterion given in Table 11. It is seen that the morning values were usually the lowest, rising until about noon. The differences are, however, comparatively small in most cases, and seem not to be markedly influenced by the meal taken about noon. The coefficient of variation (V) in the day-series is seen to vary between 5 and 30 per cent, with the mean variability 10 per cent.

Further, *double determinations* were carried out on 23 boys with an interval of some days, all tests being made in the morning. In most of the cases the maximal performance was also estimated. From these pairs of estimations the *retest-reliability coefficient* (r_{11}) was calculated for all the criteria used (cf. p. 107), with the results given in Table 12. The reliability coefficient gives an estimate of the random variations of the method and the individual factors affecting the score. To get from this an estimate of the effect of these errors in producing divergencies of obtained scores from their true counterparts, the *standard error of a single score obtained* ($\sigma_{1\infty}$) is calculated according to the formula (Garret, 1947)

$$\sigma_{1\infty} = \sigma_1 \sqrt{1 - r_{11}}$$

where σ_1 = the standard deviation of the test scores. This "standard error of

Table 11. *Daytime Variations of Scores of Physical Fitness (Product Criterion,* kg.m).

Time of Day / Subject	8—10 a. m.	10—12 a. m.	13—14 p. m.	14—16 p. m.	M	σ	V $\frac{\sigma}{M} \cdot 100$
R.F.	2,600	2,850	2,900	2,650	2,750	147	5.3
G.Ö.	1,200	1,300	1,450	1,350	1,330	104	7.8
G.H.	1,150	1,950	1,350	1,600	1,510	345	22.8
T.J.	1,900	—	2,150	2,000	2,020	126	6.2
B.G.	1,900	1,950	1,950	1,800	1,900	123	6.5
L.O.A.	2,100	—	2,200	2,200	2,170	82	3.8
C.K.	550	750	1,000	—	770	225	29.2
J.D.[1]	1,600	1,600	1,900	—	1,700	173	10.2
B.N.[1]	1,700	1,700	1,500	—	1,630	116	7.1
Ö.S.[1]	1,250	1,250	800	—	1,100	260	23.6
L.T.[1]	1,800	1,900	1,600	—	1,770	153	8.6
						Mean:	9.9

[1] Received 4 g of calcium gluconate between the first and second test. See p. 144.

measurement" may also be expressed as a percentage of the mean of the scores in the group, see Table 12. It is evident that the scores of *maximal performance* obtained on this material are provided with the greatest errors, both relatively and absolutely. The *pulse rate criterion*, in spite of the low reliability coefficient, gives the least effective error of the scores obtained.

In the important question of how high the self-correlation of a test must be to be considered satisfactory, Garret states that in order to distinguish reliably between the means of two relatively small groups of narrow range of ability the reliability coefficient need be no higher than 0.50 or 0.60. If the test is to be used to differentiate between the individuals in the group, however, its reliability should be 0.90 or more. *Thus, for the purpose of the present investigation, the reliabilities of the fitness tests employed may be considered satisfactory.*

The maximal correlation a given test is capable of yielding between the obtained scores and their theoretically true counterparts may be found by the formula

$$r_{1\infty} = \sqrt{r_{11}}$$

in which r_{11} = the reliability coefficient, and $r_{1\infty}$ = the maximal correlation between obtained and true scores (*index of reliability*). For the product criterion test, for instance, the maximal correlation should be $\sqrt{0.95} = 0.97$; when the means of the day-series reported in Table 11 are taken as estimates of the "true" scores, the correlation between these mean values and the corresponding observations is found to be 0.95 ± 0.02.

Table 12. ***Reliability and Validity of the Fitness Tests.***

Criterion	Reliability Coefficient	Standard Error		Correlation to Max. Performance	
		Absolute Value	Per Cent of Mean	Obtained Value	Corrected Value
Maximal Performance (kg.m)	0.64	470	16	—	—
Product Criterion (kg.m).	0.94	130	10	0.40	0.52
Pulse Rate Criterion (Beats/min.)	0.74	6	4	—0.40	—0.58
Pulse Pressure Criterion (mm. of Hg)	0.80	5	8	—0.25	—0.35

The correlation to maximal performance. The *validity* of every sub-maximal work test for assessment of physical fitness must be controlled with respect to the correlation to the maximal exercise performance. The inherent uncertainties in determining the latter on this special material are mentioned previously, and it may be expected that *the correlation obtained is not the true value particularly due to the error of this variable.* On a selected material of adults C. Taylor (1944) found the retest reliability for time-run to exhaustion on a tread-mill to be as high as 0.95, while the corresponding reliability on this material is only 0.64 ± 0.14.

Estimations of maximal performance were regularly made on all children during the first two series (January and May, 1946), later, after some cases of acute over-exhaustion, only random samples from some of the groups were tested. A total of 146 maximal performance tests have been made, on about 80 boys, and the coefficients of correlation for the different criteria from the whole material are given in Table 12, column four.

As the maximal performance criterion as well as the different sub-maximal tests are both unreliable, the correlation between the tests and their criterion is reduced. In order to estimate the highest correlation the test could theoretically yield between the true scores of these measures, the formula of *correction for attenuation* may be applied, which takes account of the unreliability in both sets of measurements (cf. Garret, p. 396):

$$r_{\infty\infty} = \frac{r_{12}}{\sqrt{r_{11} \cdot r_{22}}}$$

in which $r_{\infty\infty}$ = correlation between true scores in tests 1 and 2, r_{12} = correlation between obtained scores in tests 1 and 2, r_{11} and r_{22} = the reliability coefficient of test 1 and 2, respectively. The corrected values obtained are given in Table 12, last column, and it is seen that *the pulse rate criterion is likely to yield the best estimates of maximum performance*, and the value actually found (— 0.58) is in close agreement with the correlation found by C. Taylor (1944, cf. p. 130).

It is seen that the pulse rate criterion is as effective as the product criterion in estimating the fitness for heavy exercise even if the correlation actually obtained is used. The pulse pressure criterion has a very small validity in predicting maximal performance.

The relation to body constants. The scores of fitness obtained for every boy by the product criterion have been correlated to body weight, body height, body surface and calf circumference. In this material there was in no case any significant correlation, the highest coefficients obtained were for the body height (0.34 ± 0.09) and the body weight (0.28 ± 0.10). The assumption was made *a priori* that the score per kilogram body weight, i. e., the quotient relative performance (kg. m)/body weight (kg.), could be used as a "*fitness index*" *of the subject,* indicating the height (m) to which, under the given conditions he could lift his own body weight until the cardiovascular stress rose to the level corresponding to the approximate minute volume factor of 10,000. As, however, the material represented in these series was so homogeneous with respect to the body weight it was considered unnecessary to make any such "corrections". The correlation between the relative working capacity, expressed as kilogram-meters of work performed, and the "fitness-index" in meters was as high as 0.94 ± 0.01.

Comments. Instead of using the product of pulse rate and pulse pressure for the product criterion, there has also been employed, in some of the series, the product of the LILJESTRAND—ZANDER factor (i. e., the reduced pulse pressure, p. 132) and the pulse rate. The correlation between the scores obtained in this way and the scores obtained by the direct product was however 0.87 ± 0.03, and the validity was not significantly affected. As the LILJESTRAND—ZANDER factor includes more calculations it was considered more suitable to make use of the simpler direct product.

A practical and reliable indicator of the sensitivity of fitness tests is the influence of a chill (see H. L. TAYLOR and BROZEK, 1944; C. TAYLOR, 1945). A considerable decrease of the score was observed in several cases during this investigation in connection with such unpleasantness of the subject, and one case of convalescense from chicken-pox was also clearly indicated by a remarkably low score.

Results.

The results obtained by the *product criterion* on working capacity are summarized in fig. 44, in the same kind of statistical diagram as was previously used. The ordinate, relative working capacity, gives the amount of work performed until the product of pulse rate and pulse pressure during the continuously graded work on the bicycle ergometer reached the fixed value 10,000. The height of the rectangle shows the range within which the real mean value of the group

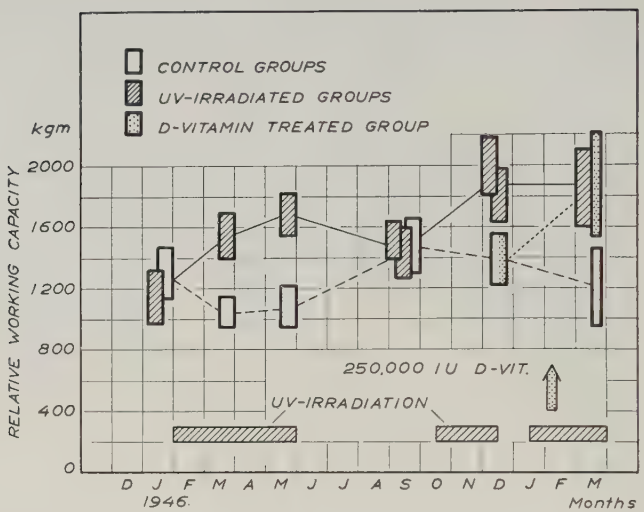

Fig. 44. The seasonal course of the amounts of work performed on the ergometer before the product of pulse rate and pulse pressure reached the value of 10,000 (relative working capacity).

is to be situated with the probability of 90 per cent, as determined with the aid of the *t*-test (p. 108). The number of determinations in every group, approximately indicated by the width of the rectangles, has usually been about 25 (see Table 10, p. 129). The data refer only to 10—11 year-old boys.

It is evident that *the ultraviolet irradiation of the children obtained by the UV-illumination system in the classrooms markedly increased the amount of work they could perform before this sub-maximal level of cardiovascular stress was reached.* The effect is highly significant; the difference between irradiated and control groups in the late spring months 1946 is 56 $\pm$ 7 per cent of the mean of the latter group.

In contrast to the irradiated group, the *control group* of the first term (Group II, see fig. 29) showed a significant decrease of the score between the first and second series of determinations (January and March, 1946). During the summer months a significant increase occurred. The control group of the following period (Group III, fig. 29) showed, with a high degree of significance (P = 0.01—0.05), some decrease between the means of September 1946 and March 1947. The significances of these seasonal variations within the same groups have been evaluated with respect to the correlation between the

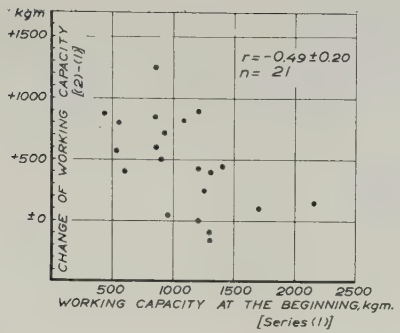

Fig. 45. The relation between the increase of score and initial score (product criterion) in the irradiated class (Group I) during the first months of irradiation.

samples (see p. 109), and they are not clearly estimable from the diagrams.

Thus, it is indicated that the relative working capacity of the control children was subject to a *seasonal variation* with a *minimum during the spring months and a maximum in the autumn.*

This annual course is the one expected if the "solar accumulation" in the body is a dominant factor (p. 124, fig. 39), and the effect of the artificial ultraviolet irradiation during the winter could then be schematically interpreted as a counteraction of a commonly occurring "winter-" or "spring-fatigue" due to the absence of natural ultraviolet radiation. However, an interpretation of the seasonal variation recorded as solely due to solar ultraviolet radiation must be made with great caution; the significant decrease obtained between the first two determinations may also be due to the experience of the test acquired by both the subjects and the operator during these first stages of its application — overlapped in the experimental group by the heavily increasing effect of the irradiation — and the increase during the summer may also be due to the growth of the children or to the physical exercise of the holidays. The decrease of the mean score of the control group during the last three series is only "probable". Thus, the existence of a solar-influenced seasonal variation of physical fitness must not be considered conclusively proved by these findings only, but such an assumption is supported by the obvious effect of the ultraviolet radiation, as well as by the fact that the irradiated group did not show any significant variation during the summer holidays.

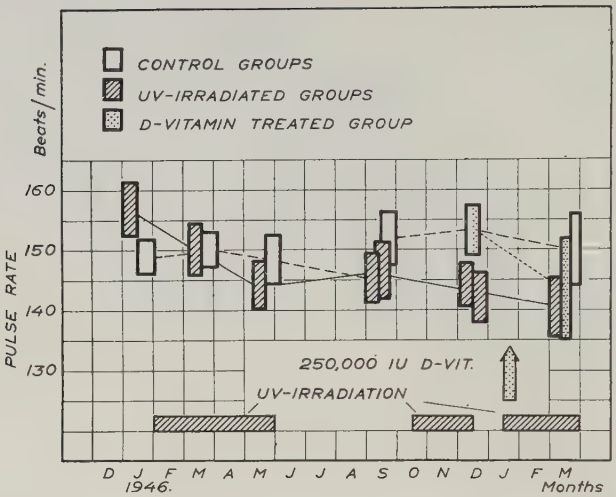

Fig. 46. The seasonal course of the pulse rate after a moderate constant amount of work on the ergometer.

The results of the irradiation during the second period (September—December, 1946) indicate an increase even beyond the normal high autumn level of relative working capacity. The same tendency is also observed when the scores are reduced to score per kilogram body weight ("fitness-index", see p. 139), i. e., the effect may not be attributed to the growth of the children.

In fig. 45 the *increase of score* of each irradiated child, obtained by the product criterion for the period between the first and second administration of the test (Jan. and March, 1946), is plotted against the corresponding *initial score value.* It is indicated that the irradiation primarily affected the children with low initial scores, while children with high initial scores were less if at all affected.

Fig. 46 gives, in a similar way, *the scores of pulse rate* after a standard amount of moderate work on the ergometer (1,000 kg. m performed in 5 minutes). By using this simple but reliable indicator of fitness there is also *clear evidence for a favourable effect* of the irradiation. When the differences obtained for the same group between different series of tests are statistically treated, i. e., when account is taken of the correlation between the samples, a significant decrease of the pulse rate score of the experimental groups is found during both the

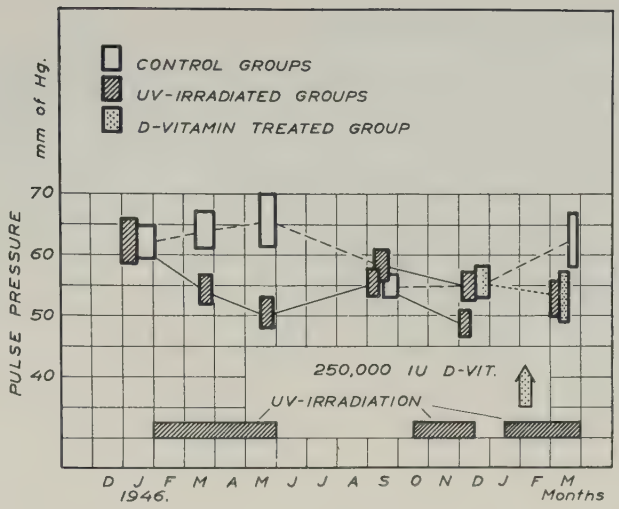

Fig. 47. The seasonal course of the pulse pressure after a moderate constant amount of work on the ergometer.

spring and autumn periods of irradiation. The scores of the control groups remained about constant in all the tests, thus indicating no seasonal variation of the pulse rate score after moderate exercise in normal children.

Finally, fig. 47 gives the variations obtained of the *pulse pressure score*, i. e. the pulse pressure measured after 1,000 kg. m of work had been performed in 5 minutes. The effect of the ultraviolet irradiation applied is apparent, and there is also strong evidence in favour of a seasonal variation of this cardiovascular response on submaximal exercise. As a measure of fitness, however, this criterion is less reliable than the others (p. 138). An interpretation of the material has shown that the pulse-pressure diminishing effect of the irradiation or, generally, all the variations observed on the pulse pressure scores, are almost entirely due to *the systolic blood pressure*. The diastolic pressure after the 5 minutes of work was remarkably constant in all the individuals, varying only between the limits 80—85 mm of Hg. It seems probable that the sense of effort and bodily strain during exercise depends, to some extent, on the height of the pulse pressure or the systolic blood pressure, and consequently, the irradiation may have a favourable influence in this respect.

The Vitamin D Experiment.

The effect of the massive dose of vitamin D (calciferol) administered *per os* to every second boy of the control Group III at the beginning of the spring term 1947 is showed by the pointed rectangles in figs 44—47. *It seems highly probable that the same effect obtained by the ultraviolet irradiation was also gained by the vitamin D treatment.* The significance of the difference between the two halves of the class using the product criterion as fitness-measure corresponds to a probability of 0.01—0.001 that the difference would be caused by chance. By using the pulse rate criterion there was also a significant effect of the vitamin D treatment; the mean decrease of the pulse rate for 9 boys tested both before and after the administration of the vitamin was 19 beats/min. with the standard error 3.5, thus giving a critical ratio, t, equals 5.4, which corresponds to a probability < 0.01 for a difference by chance. The reason why this high degree of significance is not so apparent in the diagram, fig. 46, is obviously the high correlation between the individual scores in the two samples. The pulse pressure criterion also showed a highly significant effect of the vitamin D treatment. It should be pointed out that the differences obtained cannot be ascribed to a psychological influence, as the control children were given sham-doses (paraffin oil) in the same manner and at the same times as the experimental children had their vitamin doses.

As in the case of the lack of an effect of the vitamin administration on the blood constituents it must, however, also be emphasized here that the material treated has been too small to permit a general conclusion regarding the influence of vitamin D on the performance of physical work.

A calcium ingestion experiment. In order to study whether an elevated level of total calcium in the plasma may affect the point scores of the test, four out of the eleven boys studied for possible daytime variations (p. 137, Table 11) were given 4 g of calcium gluconate *per os* between the first and second administration of the test. By repeated analyses of the blood an increase of the plasma level of calcium was found by, on the average, 0.5 mg % two hours after the calcium ingestion. There was in no case any effect observed on the score points of the test.

Discussion.

It is shown that a continous low-intensity ultraviolet irradiation of school children, applied by means of the special UV-illumination system employed, markedly increased the scores of physical fitness of the children, as estimated by a battery of submaximal cardiovascular tests. The effect was particularly pronounced during the winter and spring months when there was a tendency for a decreasing score among the control children. The summer vacation was followed by a significant increase of score for the control children but did not influence the previously irradiated children. Further it has been shown very probable that the same effect obtained by the irradiation is also reached by the administration of a massive dose of vitamin D (calciferol) in the mid-winter.

In interpreting these findings it is suitable to distinguish between the two questions involved, i. e., firstly, the *effect of the artificial irradiation* on fitness and, secondly, the *prevalence of a seasonal variation* of fitness among normal children.

The significance of the irradiation effect is without doubt and the present findings are only to be added to the previous studies carried out (Lehmann and Szakall 1932 a–b, 1944; Moschkowsky, 1936; Parade and Otto, 1939; and Allen and Cureton, 1945). An important conclusion from the present study is, however, that *the fitness-improving effect of ultraviolet irradiation may also be obtained by sub-erythemal exposures.* Lehmann and Szakall in the later paper (1944) stated, indeed, that an erythema of the skin was necessary for an effect, and the irradiation effect is assumed to be due to erythemal substances liberated in the skin. Parade and Otto on the other hand assumed the effect to be due to formation of vitamin D, acting upon the adrenal cortex. The vitamin D experiment carried out in the present investigation strongly supports the assumption of a vitamin D action, and the possible role of erythema seems doubtful.

The *hypothesis of a vitamin D action* is of interest to combine with the studies carried out by Räihä et al. (1937), later extended by Peitsara (1944), regarding the influence of vitamin D on the metabolic processes and the working capacity of isolated muscles. The importance of phosphorus for the energy-liberating chemical processes involved in the muscle contraction is a well-known fact, as well as the importance of vitamin D for the internal phosphorus

metabolism. There is, however, besides the above mentioned studies, comparatively little work carried out on the influence of vitamin D on muscle work and muscle metabolism, in spite of the apparent muscle hypotoni associated with rickets (for literature see PEITSARA, 1944). In recent reviews of physical performance in relation to vitamins and diet (KEYS, 1943; HENSCHEL, 1943), the vitamin D is not even mentioned.

The results obtained by RÄIHÄ et al., and PEITSARA may be briefly summarized as follows:

1. Tetanus-stimulated normal muscles of young rabbits or dogs show a marked increase of inorganic phosphorus and a moderate increase of hexose phosphates during the work. In rachitic muscles the increase of the concentration of hexose phosphates is much greater than in normal muscles, with a corresponding decrease in the liberation of inorganic phosphorus. No difference of the initial concentration of the phosphate-spenders (i. e., phospho-creatinine and adenosintriphosphate) was observed between the normal and rachitic muscles.

2. The administration of a large dose of vitamin D to the rachitic animals immediately (after one day) breaks down this accumulation of hexose phosphates in the muscles. Such a high dose of vitamin D to normally-fed rabbits also counteracts the moderate accumulation otherwise occurring in their muscles during the work. The concentration of inorganic phosphorus is markedly increased in both of these cases.

3. The strength and working capacity of isolated muscles from rachitic dogs are considerably smaller than for healthy dogs (PEITSARA). A large dose of vitamin D restores the working capacity in a striking manner to the normal value, or even higher, the effect appearing after only one day.

These studies indicate that one of the actions of vitamin D in the body is an *activation of the breakdown of ester phosphates* accumulating in the muscles during work, which at least in rachitic animal is followed by an increase of the working capacity of the muscle. That vitamin D in some way favours the conversion of organic phosphorus to inorganic is also reported by COHN and GREENBERG (1939). Some connection may exist between the vitamin D influence and the possible benefit to physical performance derived from high phosphate intakes which has been claimed especially by German authors (see BAUR, 1936; ATZLER, 1939); KEYS (1943) gives a critical review of this particular field.

There are also, of course, other possibilities for the explanation of the ultraviolet irradiation effect on the criteria used in the sub-maximal tests applied. The cause of the action may be sought in each of the five primary factors pre-

viously mentioned as affecting the working capacity of an individual (p. 130); the influence of psychological factors, however, may be regarded as sufficiently eliminated. The possibility of an effect on the cardiovascular system ought to be considered. It has been known for a long time that ultraviolet irradiation causes a decrease of the systolic blood pressure, which effect is usually ascribed to the vaso-dilating effect of liberated erythemal substances (JOHNSON, POLLOCK, MAYERSON, and LAURENS, 1936). In spite of a visible erythema of the skin there may be a vaso-dilating action of irradiation on deeper organs, as the muscles, giving better conditions for the performance of work. The increase of the calcium level in the blood caused by the irradiation may affect the nervous irritability and also slow down the pulse rate, thus giving a smaller response on the stress of the work. In fact, MARTIN (1939) has reported that the daily ingestion of calcium gluconate expedites the recovery from exercise, but no convincing data have been presented (see KEYS, 1943). That a single, high dose of calcium gluconate, giving a rise of the plasma calcium level by about 0.5 mg % did not markedly affect the scores of the present tests in the children is previously mentioned.

Regarding the question of a possible *seasonal variation* of the efficiency and capacity for performing physical work the present investigation has definitely shown a marked increase occurring during the summer vacation of the children, but an actual decrease during the winter may not be regarded as conclusively proved, the probability however being comparatively high. *The most rational explanation*, covering all the results obtained on the variations of the working capacity in the children, would obviously be the following. The vitamin D supply of a child's body is continuously decreasing during the winter, when the consumption of the vitamin is greater than its solar formation. This decrease is followed by some decrease of the physical working capacity, and the minimum is noted in the break between winter and spring when the accumulation of the solar-formed vitamin would have its minimum (HORSTMANN and PETERSEN, 1946, cf. p. 124). Artificial ultraviolet irradiation during the winter completely counteracts this seasonal variation, maintaining the capacity at the normal autumn level throughout the year. The same effect may also be yielded by a sufficient administration of vitamin D in the diet, thus indicating that the effect of the irradiation is due to the photochemical formation of vitamin D.

An important consequence of this interpretation is that *a reduction of working capacity, as estimated by cardiovascular criteria in submaximal work tests, is a sensitive sign of vitamin D deficiency* and that the supply of this vitamin during the winter is not sufficient to main-

tain an optimal condition for physical work in children. The latter conclusion was also reached by the interpretation of the results obtained for the seasonal variations of calcium and phosphatase levels in the blood, though the active principle in this case may also be other solar-formed substances than the vitamin D.

The comparatively low scores of physical fitness found in spring may be set in connection with the common layman's experience of a "*spring-fatigue*". All kinds of vitamin have been claimed as treatments for this, but vitamin D undoubtedly least of all. The results obtained here indicate indeed that some part of the commonly-experienced body fatigue in spring is *an after-effect of the poverty of solar radiation during the preceeding winter*. The great popularity of a short holiday in the mountains in spring may be considered to originate in some way from the experience of a favourable influence of the intensive solar radiation; even without actual physical exercise, skiing etc., such a holiday is said to be "health-improving". It also seems probable that the general "tonic" effect of artificial ultraviolet irradiation during the winter depends to a large extent on this affect on the physical fitness. Furthermore, many doctors are claiming for a wholesome influence of cod liver oil during the winter in older children also, and one of the reasons may be the experience of an improvement of physical fitness.

To sum up, the investigation has shown that the solar radiation climate of the latitudes of Sweden is not sufficient in the dark season to maintain an optimal condition in the body for performing physical work, the reason probably being the reduction of vitamin D in the body during the winter. The UV-illumination system has proved to be an effective substitute in this respect.

CHAPTER 12

Effect on Air-Borne Bacteria.

The spectroradiometric analysis of the radiation emitted by the medium-pressure mercury lamp employed for the UV-illumination indicated comparatively strong intensities of radiation in the spectral region below 290 mμ, i. e., radiation with high bactericidal effect.

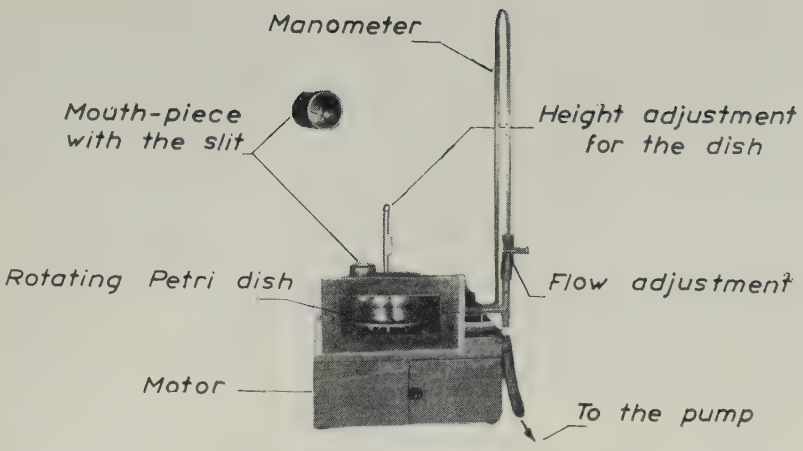

Fig. 48. The air-sampler used for determinations of bacterial concentration.

Most of the energy in this region is concentrated at the wavelength 265 mμ (see fig. 7, p. 64), which coincides with the region of highest sensitivity of typical bacteria (cf. HOLLAENDER, 1942).

The investigation of the bactericidal action of the UV-illumination has comprised a laboratory study, made in a small infection-chamber permitting exact control of temperature, humidity and bacterial concentration, and further determinations of the total count of bacteria in illuminated and control classrooms during the lessons. By "total count" is meant the number of colonies which are formed on ordinary blood agar plates by exposure in the air-sampler. Finally, a physical interpretation of the bactericidal effect is carried out, with a comparison between the effect of the partial air irradiation usually employed for the bactericidal, low-pressure mercury lamps and the more uniform irradiation of the room which is obtained with the UV-illumination system.

Method of Air-Sampling.

The concentration of bacteria in the air has been determined by means of an impinging device of the type slit-sampler, constructed at this Institute after an original model designed by BOURDILLON et al. (1941). The apparatus has been previously described by LAURELL, LÖFSTRÖM, MAGNUSSON, and OUCHTERLONY (1947). Fig. 48 shows its features. The chamber contains a slowly rotating table carrying a petri dish with agar, on which the air impinges through a slit in the bottom of the metal cylinder (mouth-piece);

the slit coincides with the radius of the petri dish. The distance between the slit and the surface of agar is adjustable and is indicated by a metal rod which rests on the agar surface (height adjustment). The distance 2 mm was used according to the recommendation of BOURDILLON. The front wall of the chamber consists of an airtight window through which the plates can be changed. The chamber has two outlets, the one attached to a manometer and the other to a suction pump. The rate of flow through the chamber was adjusted to about 35 litres per minute as determined by a flow meter, and it was found that the rate for a given manometer reading was reproducible if the slit was kept perfectly clean. Each plate was exposed for 3 minutes. The nutrient was in all cases ordinary 10 per cent blood agar; no selective culture media were employed. The plates were incubated for 24 hours before counting the number of visible colonies formed during the exposure.

The Infection-Chamber Experiments.[1]

The laboratory control of the bactericidal effect of the UV-illumination was carried out by means of a 30 m^3 chamber for artificially infected air, with 3 m ceiling height. The chamber was equipped with a complete air-conditioning system which permitted an exact control of temperature and humidity. The air-sampling device was situated outside the chamber and the inlet tube was drawn through the wall so that the sampling could be made from different parts of the chamber. Liquid suspensions of bacteria were sprayed into the chamber by an atomizer and a centrally placed electric fan provided for a homogeneous suspension of the infected air. The injection of bacteria was stopped when the concentration had rised to a suitable level, and the fan was turned off after some minutes. From then the air-sampling was made every 30 seconds. The settling rate of the bacteria was measured in a number of experiments. During the first 10 minutes there was usually a reduction to only about 90 per cent of the initial concentration.

For the tests on the UV-illumination a complete fixture (UV-source + incandescent lamps + reflector) was mounted at ordinary height in the chamber. The illumination was turned on one minute after that the fan had been switched off.

Tests have been made with a number of different bacteria, and

[1] These experiments were made in collaboration with Dr G. LAURELL, Public Health Institute, Department of Public Hygiene, Stockholm. They will be reported more completely in later papers.

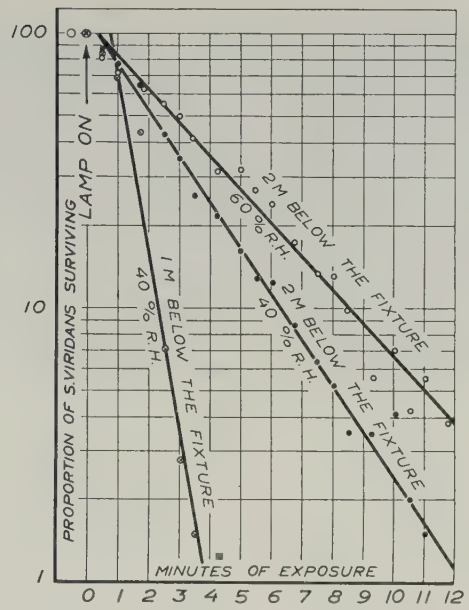
100
10
1
PROPORTION OF S.VIRIDANS SURVIVING LAMP ON
MINUTES OF EXPOSURE
0 1 2 3 4 5 6 7 8 9 10 11 12
2 M BELOW THE FIXTURE
60 % R.H.
2 M BELOW THE FIXTURE
40 % R.H.
1 M BELOW THE FIXTURE
40 % R.H.

Fig. 49. The reduction of bacterial concentration in the air at different distances below an equipment of the UV-illumination. Test bacterium was *S. salivarius* (*S. viridans*).

a strong bactericidal effect of the illumination was evident in all cases. When using, e. g., *Staphylococcus albus* as test bacterium it was found that the air was practically sterilized in the chamber within the first minute after the lamps had been turned on. The bacterium finally selected for the tests was the more resistent *Streptococcus salivarius* (a variety of α-haemolytic streptococci).

Fig. 49 shows some of the data collected in these experiments. Every dot is the mean of four separate series of determinations made subsequently with reinfected air for every series. Data were in this way collected for relative humidities between 30 and 80 per cent, and with the inlet to the air-sampler placed at different distances and directions from the equipment.

It is seen that the reduction of the bacterial concentration follows an almost straight course when plotted in the semi-logarithmic diagram, i. e., the exponential relationship between survival-ratio and exposure holds approximately for the range of interest for practical purposes. A reduction to 10 per cent of the initial concentration is reached within about 5 minutes in the air 1—2 m below the fixture.

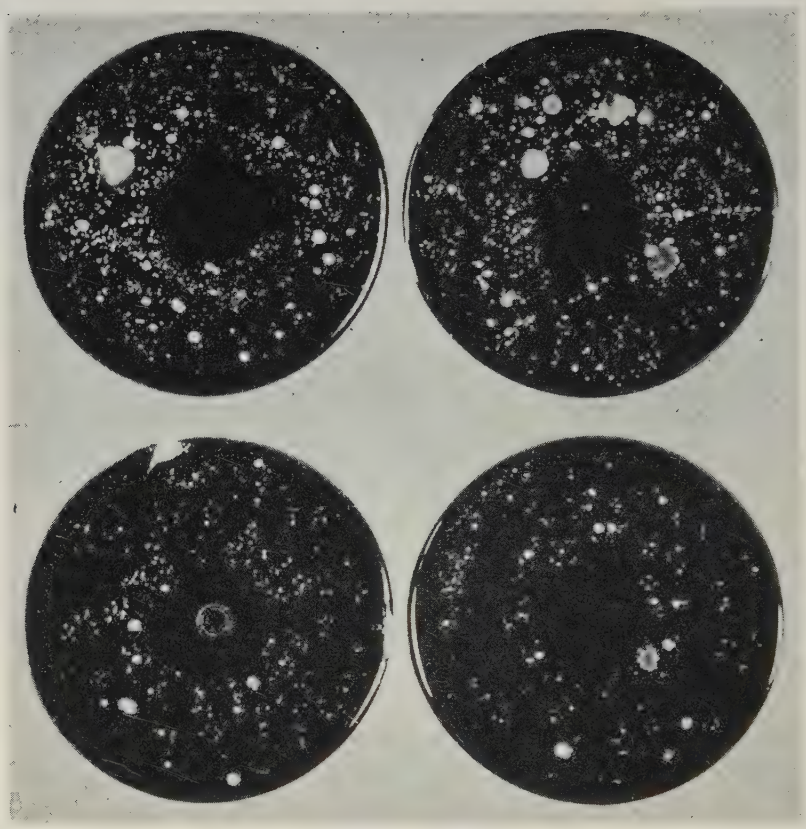

Fig. 50. Blood-agar plates exposed to 100 litres of air in classrooms. The upper two are from a control classroom and the lower two from a classroom equipped with the UV-illumination system.

The killing rate is somewhat smaller in the first minute of irradiation, which is obviously due to the lower ultraviolet output of the mercury lamp before it has reached the normal operating conditions.

The influence of humidity is demonstrated in the figure, and the findings here agree in principle with previous observations (see, e. g., Wells, 1940).

The Effect in the Classrooms.

Determinations of the concentration of bacteria in the air in classrooms have been made in the spring term 1947 during 20 lessons, 9

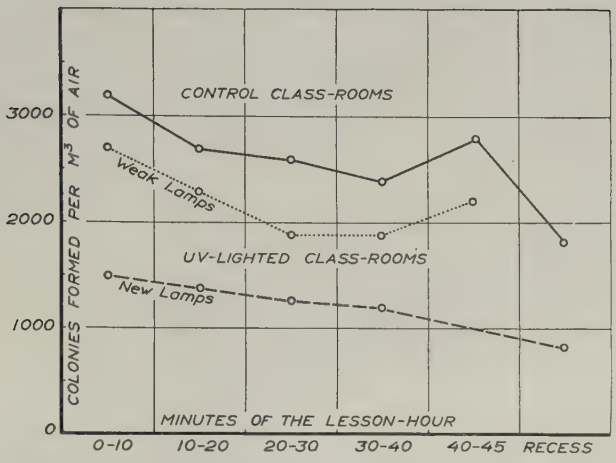

Fig. 51. Mean bacterial counts found for different periods of the lesson-hour in classrooms with different illumination conditions.

of which have been made with the UV-illumination turned on and 11 without UV-illumination. During each lesson about 7 plates were exposed to 100 liters of air for 3 minutes in the air-sampler described above. The samples were taken at 1—1.5 m above the floor among the children. Fig. 50 shows some typical examples of plates obtained in different classes.

The general feature of the bacterial density in the air during the course of the lessons is an immediate and marked increase in the few minutes when the children rush into the room after the break. The concentration may then reach as high as 4,000 bacteria per cubic meter of air, but is usually decreasing slowly during the lesson; the last minutes are often characterized by a new moderate rise. The absolute level is to some extent dependent on the general activity in the classroom; a noisy lesson always gave higher values than a quiet lesson. The ventilation during the recess did not give a complete reduction of the bacterial density; the low temperature outdoors in the winter and spring when the determinations were made did not permit much ventilation. The average counts found for different times of the lesson and for different illumination conditions are given in fig. 51.

In the classrooms equipped with UV-illumination determinations have been made both with and without the illumination turned on.

Table 13. *Total Count of Air-Borne Bacteria in Control and UV-illuminated Classrooms during the Lesson-hours.*

Classroom	Number of lessons	Number of plates exposed	Mean count per 0.1 m^3	Standard deviation
1. Control	11	48	271	63
2. UV, weak lamps	4	24	212	56
3. UV, new lamps	5	27	136	53

Difference 1—2 = 59 ± 14; t = 4.2
1—3 = 135 ± 13; t = 10
2—3 = 76 ± 15; t = 5.1

The concentrations found without the illumination did not differ from the counts found in control classrooms without UV-equipments.

The data given in fig. 51 show an apparent effect of the UV-illumination. The average counts for the lesson-hours found in controll classrooms and experimental classrooms for the whole period of determinations are given in Table 13, with the corresponding statistical data. The differences are clearly significant. *With new ultraviolet sources a reduction to about one half was found for the total bacterial content in the air of rooms with UV-illumination.* With lamps which had burned for more than 300 hours the effect was considerably smaller.

Physical Interpretation of the Bactericidal Effects.

The following account of the physical factors determining the disinfection of air by irradiation is mainly based on the principles developed by W. F. Wells in a number of papers (Wells, 1940, 1944, 1945). Other treatises which have been consulted are those by Buttolph (1944) and Luckiesh and Holladay (1942, see also Luckiesh, 1946). The interpretation carried out here summarizes, partly in a new form, the basic equations of radiant air-disinfection, but the main purpose is to show the potentialities of the UV-illumination system in this respect, compared with the upper-air irradiation by means of the bactericidal, low-pressure mercury vapour lamps.

The evaluation of bactericidal energy is made by weighting the

spectral intensities of the radiation with the bactericidal action spectrum (cf. Table 1, p. 52). The action spectrum employed is that given by HOLLAENDER (1942) as typical for most bacteria. The weighted radiation is denoted by UVG.

The Basic Principles.

The following notations are used:

UVG = ultraviolet radiation weighted by the bactericidal action spectrum,
P_0 = initial concentration of bacteria ($t = 0$),
P = concentration at the time t,
t = time of exposure in minutes,
E = intensity of UVG in mW/m²,
F = flux of UVG in mW,
V = volume of irradiated air (m³),
R = ray length in the irradiated air volume (m),
U = unit lethal exposure, mWmin/m² (see below),
N = equivalent number of air-changes, and
α = air-clearence of the irradiation (m³).

ln denotes the logarithm to the base e, and log denotes the logarithm to the base 10.

Surface disinfection. It is repeatedly found that for practical purposes the reduction of bacterial concentration on a surface when exposed to bactericidal irradiation follows an exponential relation according to

$$\frac{P}{P_0} = e^{-kEt} \tag{1}$$

When the dosage Et equals $\frac{1}{k}$ it follows that $\ln P/P_0 = -1$, and $P/P_0 = 0.368$, i. e., this dosage gives a survival ratio of 36.8 per cent of the bacteria. It is called the *unit lethal exposure* or lethe (WELLS and WELLS, 1938). In the following it is denoted as U and is expressed in the units mWmin/m². Introducing this entity in equation (1) yields its definite form:

$$\frac{P}{P_0} = e^{-\frac{Et}{U}} \tag{2}$$

Determinations of unit lethal exposure have been made for a number of different bacteria (see HOLLAENDER, 1942). The values are, for most bacteria, influenced by the humidity of the air or the surroundings. For *E. coli*, which has been most used as test bacterium, WELLS (1945) gives the average value for moderate humidity of 2 μWmin/cm² (20 mWmin/m²) of radiation of wavelength 253.7 mμ, and it is found that the sensitivity of ordinary respiratory bacteria in saliva is about the same, or rather somewhat smaller (LUCKIESH, TAYLOR,

and KNOWLES, 1947). Moulds and dustborne bacteria are, on the other hand, 500—1,000 times more resistant. BUTTOLPH (1944) calculates for practical purposes with the unit lethal exposure equal to 10 μWmin/cm^2, and LUCKIESH (1946) uses 5.0 μWmin/cm^2. The latter value is tentatively applied here as an average for air-borne pathogenic bacteria.

Equation (2) may also be written

$$Et = U \ln \frac{P_0}{P} = 2.303\, U \log \frac{P_0}{P} \tag{3}$$

Thus, a reduction from an initial concentration of 100 per cent to the concentration 10 per cent requires about 2.3 times higher dosage as the unit reduction to 36.8 per cent; the reduction to 1 per cent requires about 5 times the value of U (cf. BUTTOLPH, 1944).

Volume disinfection. It is assumed that the bacteria are homogeneously suspended in the air volume (V) and that the radiant flux (F) which enters the volume is uniformly distributed in it and is not significantly depleted by absorption due to either the air or the bacteria. The *ray length* in the volume is R. The volume V may then be considered as built up of an infinite number of differential volumes $T dR$, thus

$$V = \int^{R} T\, dR \tag{4}$$

This relation is accurate for a parallel beam of radiation. For a divergent beam, T must of course be replaced by its function of R.
The mean intensity in the volume is determined by the mean surface of the irradiation (T_m) which is found by

$$T_m = \frac{1}{R} \int^{R} T\, dR = \frac{V}{R} \tag{5}$$

Consequently, the mean intensity (E) in the volume V by the mean ray length R is expressed by the general formula

$$E = \frac{F \cdot R}{V} \tag{6}$$

When applied to a practical case of air irradiation in a room both R and F may be different in different spaces of the room and at different angles to the source. The mean intensity is then obtained as the average of the intensities in the partial volumes ΔV of the room, for which equation (6) may be considered approximately valid, thus

$$E = \frac{\Sigma (\Delta F \cdot R)}{\Sigma \Delta V} = \frac{\Sigma (\Delta F \cdot R)}{V} \tag{7}$$

The units of E for the volume are obviously mW.m/m³ which form the general expression for the bactericidal intensity of the radiation in a volume (cf. LUCKIESH and HOLLADAY, 1942).

The reduction of the bacterial concentration in the volume is obtained by substituting this expression of E in eq. (2), thus

$$\frac{P}{P_0} = e^{-\frac{F \cdot R}{\frac{V}{U}}} \tag{8}$$

The exponent may be transformed according to

$$\frac{P}{P_0} = e^{-\frac{\frac{F \cdot R}{U}}{V}} \tag{9}$$

The term $\frac{F \cdot R}{U}$ has the units

$$\frac{\text{mW} \cdot \text{m}}{\text{mW min/m}^2} = \frac{\text{m}^3}{\text{min}}$$

and eq. (9) consequently has the character of the general equation for a dilution rate due to ventilation. *The term* $\frac{F R}{U}$ *corresponds to that ventilation rate which would give the same dilution of the bacterial concentration as is produced by the irradiation of the air.* This figurative but eloquent expression for the bactericidal effect of air-irradiation in a room was introduced by WELLS and WELLS (1938) and is termed the equivalent *sanitary ventilation.*

The expression from the exponent in eqs (8) and (9) may be used separately according to

$$\frac{F R}{U V} = N \tag{10}$$

which gives the *equivalent number of air-changes* in the room (N), which produces the same reduction of the bacterial density.

Equation (9) may be written in the form

$$\alpha = \frac{V}{t} = \frac{F R}{2.3\ U \cdot \log \frac{P_0}{P}} \tag{11}$$

which permits the computation of the volume of air (α) which can be disinfected to the ratio $\frac{P_0}{P}$ per minute of the exposure; it may be termed the *air-clearance* of the installation. This equation is particularly practicable for the design of irradiation systems in certain cases (see below).

By introducing in the equations above a unit of *bactericidal* pover (P_{UVG}) for the sources, based on the principles develoed in Chap. 4 (see p. 49) i. e.,

$$P_{UVG} = \frac{F}{U} \tag{12}$$

the formula are still more simplified and practicable. The power-value gives the area (m^2/min.) which is disinfected to the unit degree (36.8 per cent survival) if all the radiant flux (F) is concentrated on it. The formula given above for equivalent sanitary ventilation and air-clearance are easily transformed in accordance with this unit. The radiant sensitivity of different bacteria may conveniently be expressed by the relation to the average pathogenic bacteria ($U = 50$ mWmin/m^2).

From the above it is seen that the physical factors which primarily influence the bactericidal effect of air-irradiation are the flux of bactericidal radiation (F), the ray length in the irradiated volume (R), and the sensitivity of the bacteria (U). The air-clearance produced by the bactericidal irradiation varies directly with the flux and the ray length but inversely as the unit lethal exposure of the bacteria.

Applications in Practice.

The primary assumptions of a homogeneous suspension of the bacteria and a uniform distribution of the radiation in the air, made for the ideal case treated above, are not strictly valid for most cases in practice. The formula derived must, however, form the basis for the treatment here also. There are two general cases which must be treated separately. The one is the *partial irradiation of the air* in a room, which is the method employed for the low-pressure mercury vapour lamps as disinfecting source. The other case is the *uniform irradiation of the air*, which is employed with the UV-illumination as the bactericidal agent.

Partial irradiation of the air. The irradiation of the air above eye-level is the common form for the administration of bactericidal lamps in the control of air-borne infections. Only small intensities of the radiation are allowed below the eye-level, due to the high risk of eye-injury (see p. 54). Ceiling and upper walls must be painted with ultraviolet-absorbing paints (oil paints). The disinfection of the air in the irradiated zone of the room may be treated according to the formula given above. The resulting dilution of the bacterial content in the occupied region is, however, *exclusively determined by the rate of interchange of air between the irradiated and non-irradiated zones.* If there is no circulation of the air the concentration of bacteria in the occupied zone will increase independently of the disinfection taking place in the upper zone.

Determinations of effective air-circulation in different rooms have been undertaken by, among others, Wells (1945) and Luckiesh and Holladay (1942, see also Luckiesh, 1946). It is related to the rate of movement of the air in the room, which is due to its actual replacement through air ducts, windows and openings and to currents set up by differences in temperature, circulating fans, movements of its occupants, etc. Hot radiators of free situation may increase the circulation several times (cf. Luckiesh, Taylor, and Knowles, 1947), and it seems probable that cold windows may have a marked effect too.

There are obvious difficulties in measuring air circulation in occupied spaces; the principle employed is usually to measure the reduction of bacterial density actually obtained in the lower zone and from this calculate a factor for the corresponding effective circulation (see WELLS, 1945). In this way WELLS found the effective circulation between the occupied and the irradiated zone, i. e., below and above the seven-foot level (2.1 m) in standard American classrooms to exceed 4 air-changes a minute.

Such a high value of the natural circulation in a room may, however, not be found in all cases. Measurements of the air movements in Swedish classrooms, carried out during this study with the aid of the kata-thermometer according to the technique described by BEDFORD (1946), indicated a mean movement of only 2—3 m/min. at the 2 m level of the room. If the entire volume of the air is considered to be moving in an unbroken stream, rising through one half of the horizontal cross section of the room and descending through the other half, with the velocity 2 m/min., this would produce, in a room with 50 m^2 floor area, an air-circulation of 50 m^3/min. With the volume of the occupied zone equal to 100 m^3, this circulation corresponds to only about 0.5 air-changes a minute, or 30 air-changes per hour. It seems further unlikely that all of the air movements should be effective for the interchange between the upper and lower zone. It ought to be mentioned, that the radiators of the rooms during these measurements were hot, but they were shielded in cupboards in the walls with inlets for the air near the floor and outlets for the warm air near the ceiling.

The air-circulation may of course be *raised by means of fans*. The upper limit is placed by the threshold of draught (about 20 m/min. air velocity); with such an effective circulation the possible number of air-changes per minute in the case cited above would be about 5; even higher values may be obtained if the air is forced at higher velocities along walls etc.

Another factor limiting the resulting reduction of the bacterial density in the occupied zone is *the volume of the irradiated zone*. The efficiency of upper-air irradiation increases markedly with increasing ceiling height of the room (see LUCKIESH and HOLLADAY, 1942). It is found that an irradiated stratum of only about 1 foot (0.3 m) below the ceiling is insufficient to influence markedly the bacterial density in the lower part of the room (LUCKIESH and TAYLOR, 1947). The lamps must be placed about 0.5 m above the eye-level in the room in order to protect the occupants. Thus, in rooms of a ceiling height about or below 2.5 m no great effect of an upper-air irradiation may be expected.

A practicable formula for the *design of a bactericidal upper-air irradiation* of a room is offered by eq. (11) given above. The circulation, natural or forced, available in the room is the volume which should be cleared during its passage through the irradiated zone. The known or estimated value hereof is substituted for α in the equation. The value of R is dependent on the size of the room, and the radiant distribution of the reflector and may be estimated from this; the fixtures should obviously be placed so that the ray length is maximal. Then the equation may be solved for F by substituting the values of unit

lethal exposure (U) and desired degree of disinfection (log P_0/P) in the equation. By assuming U equal to 50 mWmin/m² and the degree of disinfection desired as 99 per cent (log $P_0/P = 2$), the denominator is 250, and F is obtained in milliwatts. For a 200 m³ classroom with an effective mean ray length of 4 m and 2 air-changes per min., the bactericidal flux (F) required for 99 per cent disinfection is then found to be 25,000 mW (25 W). That flux is obtained with four 30-watt germicidal lamps.

The same calculation made with the unit of bactericidal power according to eq. (12) is easily shown to be carried out by the general formula

$$P_{UVG} = \frac{5 \cdot \alpha}{R} K \tag{13}$$

where K stands for the sensitivity relation of the actual bacteria to the »average pathogenic bacteria». In the present case ($K = 1$) P_{UVG} is found to be 500 m²/min. A 30-watt germicidal lamp (total flux of UVG about 7,000 mW) correspond to a power of about 150 m²/min. (cf. Table 2 and 3, pp. 65—66).

Uniform irradiation of the air. The bactericidal radiation of the UV-illumination is distributed throughout the room, as it is combined with the visible light. However, the distribution is not perfectly uniform but determined by the intensity distribution of the reflectors (fig. 11, p. 71) and to some extent by the reflection from different surfaces. The physical interpretation carried out on the bactericidal efficiency of the UV-installations in the classrooms has been made in the following general way.

The average bactericidal intensity was calculated according to formula (7) given above, for both the region of the room above the reflectors and below the reflectors. The flux of UVG (ΔF) was calculated for every 30 degree zone around the reflector according to the method described on p. 84, i. e., from the intensity distribution curve of the reflectors, and with the total flux of UVG given in Table 2 (p. 65). The corresponding ray lengths (R) were obtained for every zone from the actual dimensions of the classrooms; the average for the measurements in four directions was used. In this way the value of $\Sigma(\Delta F \cdot R)$ was estimated to be 470 mW · m per fixture in the lower part of the rooms and 740 mW · m per fixture in the region above the fixtures. The volume of the lower part is 150 m³ and of the upper part 50 m³. The mean bactericidal intensity in the occupied zone below the four fixtures of the room is then 12.5 mWm/m³, and in the upper zone 60 mWm/m³; these intensities may also be expressed as 1.25 μW/cm² and 6 μW/cm², respectively, on the mean surface of the irradiated volumes (cf. p. 156).

However, these values give only the intensities due to the *direct radiation* from the UV-equipments. The ceiling and walls in the rooms were painted with ultraviolet-reflecting paints and add further bactericidal radiation to the air. The *reflected radiation* to be considered is that from the upper part of the room, as the lower part with the floor and furnitures may be expected to absorb most of the radiation. The reflected flux of UVG reaching the working plane of the room was calculated by means of the distribution coefficients, as described on p. 75. The coefficient of the indirect component was estimated to

be 0.2 for the UVG-radiation (cf. Table 4, p. 71), which gives a total reflected flux passing from the ceiling down to the working plane of 250 mW of UVG. The mean ray length of this reflected radiation offers considerable difficulties for the calculations. The height from the working plane of the room to the ceiling is about 3 m, but most of the radiation is diffusively passing through the air, and depleted by further reflections on the walls. The trigonometric calculation of the average distance from a point in the working plane to the ceiling, extended to include the rays reflected from the upper third of the walls, gives the value 4.4 m, which was employed for the following estimates. This ray length gives a total of 1,100 mW · m of reflected bactericidal radiation in the room. About two thirds of this radiation is effective in the lower part of the room. These considerations, which probably yield somewhat too small figures, lead to the estimates that the mean bactericidal intensity below the fixtures in the room is about 20 mWm/m³ and above the fixtures 80 mWm/m³. The disinfecting effect of these intensities may be transformed into *equivalent number of air-changes* by means of formula (10); assuming the unit lethal exposure to be 50 mWmin/m² the following values are obtained:

below the fixtures: *24 air-changes per hour,*
above the fixtures: *95 air-changes per hour.*

These figures give the sanitary ventilation produced by the radiation from the fixtures during its passage through the respective volumes. From the hygienic point of view it is the ventilation in the occupied region which is of particular interest. To the figure given above should be added the effect caused by the circulation of the air through the more strongly irradiated upper part of the room, and further the natural ventilation existing in the room. *An estimate gives a probable total value of about 30 air-changes per hour effective for the dilution of bacteria in the occupied region of the room;* at least 25 are due to the UV-illumination system and of these about 8 to the reflected radiation.

These estimates may be appropriately compared with the data obtained in the *infection-chamber experiments.* It was found (see fig. 49) that the concentration of bacteria (*S. salivarius*) in the air 1—2 m below the fixture was reduced to 36.8 per cent of the initial value in about 3 minutes. No reflected radiation was present in this case, but the intensity of direct radiation was comparable to the conditions in the classrooms. The air-change N which would produce the same bacterial reduction, is simply obtained from the formula

$$\ln \frac{P}{P_0} = -N \cdot t$$

The unit reduction ($\ln P/P_0 = -1$) in 3 minutes gives $N = 0.3$, i. e., 0.3 equivalent air-changes per minute, or about 20 equivalent air-changes per hour, which agrees well with the figure derived above.

The reduction of *total bacterial count* obtained in the classrooms cannot be used for more than a rough estimate of the killing effect on respiratory and pathogenic bacteria. The unit lethal exposures for most of the saprophytic, dust-borne bacteria always found in crowded rooms are, as mentioned above,

500—1,000 times higher than those of most pathogenic organisms. *There may be considerable reduction of the respiratory fraction of the total count without influencing to a higher extent the value of the total count.* Thus, WILLIAMS (1947) found, by upper-air irradiation of classrooms in England, a reduction of the total count by about 25 per cent, while the reduction of α-haemolytic streptococci recovered from the air on selective substrate was about 70 per cent. It seems reasonable to assume that the reduction to about 50 per cent of the total count obtained by means of the UV-illumination system was accompanied by a considerably greater reduction of the respiratory expelled bacteria.

A distinct advantage of the UV-illumination is furthermore offered by the comparatively high intensity of bactericidal radiation incident on the lower *surfaces of the room* (see Table 5, p. 77). A reduction of the bacterial content in the dust collecting at the furnitures and the floor may be expected to result from this.

Discussion.

The experimental data and the theoretical interpretation of the bactericidal effect of the UV-illumination system employed for the classrooms give evidence that *a sanitary ventilation equivalent to about 30 air-changes per hour may be produced in the occupied region of the rooms*, mainly due to the direct effect of the radiation on the air in this region. This bactericidal effect is obtained without hitherto observed risks of injury to the occupants. It is independent of the circulation of the air in the room, although an improved circulation may yield still higher bacterial reduction.

Studies of the dynamic spread of measles in classrooms have indicated that the minimum sanitary ventilation which can control this spread is about 4 m^3/min. per pupil (see WELLS, 1945). In an ordinary classroom of 200 m^3 with 30 pupils this means a minimum sanitary ventilation of 36 air-changes per hour. The UV-illumination system in the present arrangement offers a considerable part of this threshold sanitary ventilation, and increases the sanitary ventilation about 10 times as compared with the natural ventilation in ordinary Swedish classrooms. It seems possible that a new arrangement will yield still better effect than hitherto obtained (cf. p. 176).

An important field of application for the UV-illumination system as a bactericidal source is *rooms with low ceilings*. It is shown above that an irradiation of only the stratum above eye-level is insufficient to produce a marked improvement of sanitary ventilation in rooms with ceiling height below about 2.5 m. The usual ceiling height in

modern apartments in Sweden is about 2.7 m. It seems likely that the UV-illumination system may be more effective as a bactericidal agent in such rooms than an upper-air irradiation with the bactericidal low-pressure mercury lamp. Suitable applications may be found in many schools, day nurseries etc.

An inherent factor which to some extent limits the general use of UV-illumination is obviously the high wattage. A sufficient air disinfection in classrooms may be obtained by about 120 watts of low-pressure bactericidal lamps (see p. 160), while the UV-illumination consumes a total of about 2 kilowatts. However, when the day lighting in the room is sufficient for the illumination, only the medium-pressure mercury lamps may be burning, consuming in total about 500 watts in a classroom.

CHAPTER 13.

Effect on Absenteeism.

The intentions of the account given here on the influence of UV-illumination on absenteeism due to illness are only indicative. There are only three classrooms which have been equipped with UV-illumination, and the time of observation is reduced to two terms for each of the classes in these rooms. It would be premature to draw general conclusions from this material for such a variable factor as absenteeism from school, if the effect were not exclusively marked; this is, however, not the case.

In order to give a general background of the records obtained during the period of investigation for both experimental and control classes the absenteeism in all classes of 1st grade and 4th grade in Vaksala Secondary School of Uppsala has been recorded for the years 1943—1947. For each school-year and for each grade 4—5 classes (120—150 pupils) are involved in the statistics. The record is made for each week of the terms, and the data are obtained from the registers kept by the respective teachers. The registers are uniform for all classes, and absenteeism due to illness, as the reason pretended, is recorded separately from absenteeism due to other reasons.

The records are made with respect to two measures of illness-

status in the classes: *incidence of illness* and *lost time due to illness*. The second measure includes also the duration of each case of absenteeism. These two measures coincide in the main but there may be some differences also, which will be shown later.

There was from the beginning no differentiation made between boys and girls in the statistics collected here. It was, however, later made clear that the girls showed in general a higher rate of absenteeism than the boys, which must be considered in the correct statistics. All 1st classes treated, including the experimental groups, comprised about equal proportions of boys and girls and the records are sufficiently comparable for that reason. The experimental groups of 4th classes were made up of boys only during most of the investigation. The control material of the statistics given here involved both boys and girls and a comparison between the means must be undertaken with regard to this disproportion. However, the control material involved at least one class of boys only during the experimental periods, and the range of variation given for the means of different classes may be a justifiable basis for the comparison.

Cases of only one day's duration were also included in the statistics as most of such cases are really due to illness and especially respiratory illness, according to the experience of the teachers.

The responsibility of various diseases for the absenteeism cannot be obtained from the registers. In order to get an estimate of the role played by respiratory infections ("colds") for the total illness-rate, specifications of the diseases were requested from the parents of the children in three 4th classes of the Secondary school for one term (the spring term 1946). Altogether more than 200 such specifications were collected, and it was found that 84 per cent of the total number of absenteeisms during that period were ascribed to respiratory infections by the parents. Other diseases were found to be fairly uniformly distributed over the term, and, therefore, *the seasonal variations recorded may be considered as primarily due to epidemics of respiratory infections*. The role of measles, scarlatina, and other children's diseases formed a very small fraction of the total absenteeism in these 4th classes. For other years and other classes there may have been other proportions which, however, could not be taken into account. Single cases of exceptional diseases (accidents etc.) were often specially denoted in the registers and could be excluded.

The data are reproduced in the diagrams of figs 52—55. The inci-

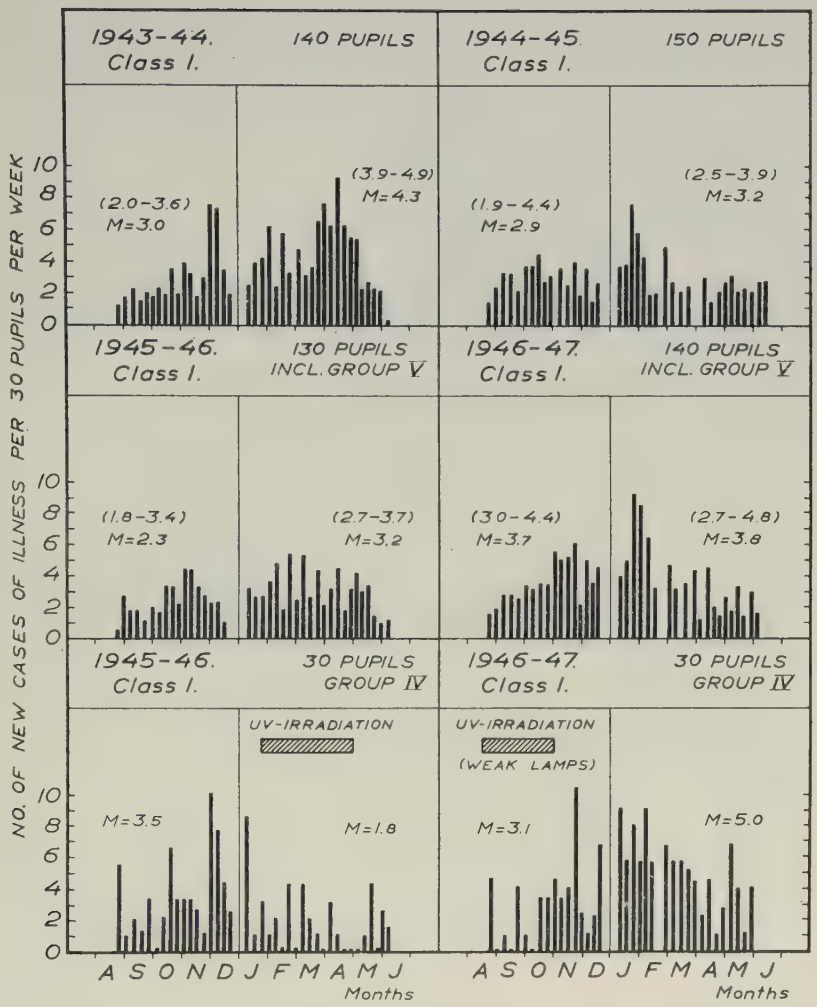

Fig. 52. Incidence of illness in 1st classes for each week of the school-years 1943—1947. Classes with UV-illumination in the two lowest squares (1945—1947).

dence of illness is given as the average number of new cases of illness per 30 pupils per week (6 days), and the time lost is expressed in school days per 30 pupils per (full) week. Every school year, comprising an autumn term between August and December and a spring term between January and June, is treated as an entity. The small figures placed in each term-square give the average for the term (M)

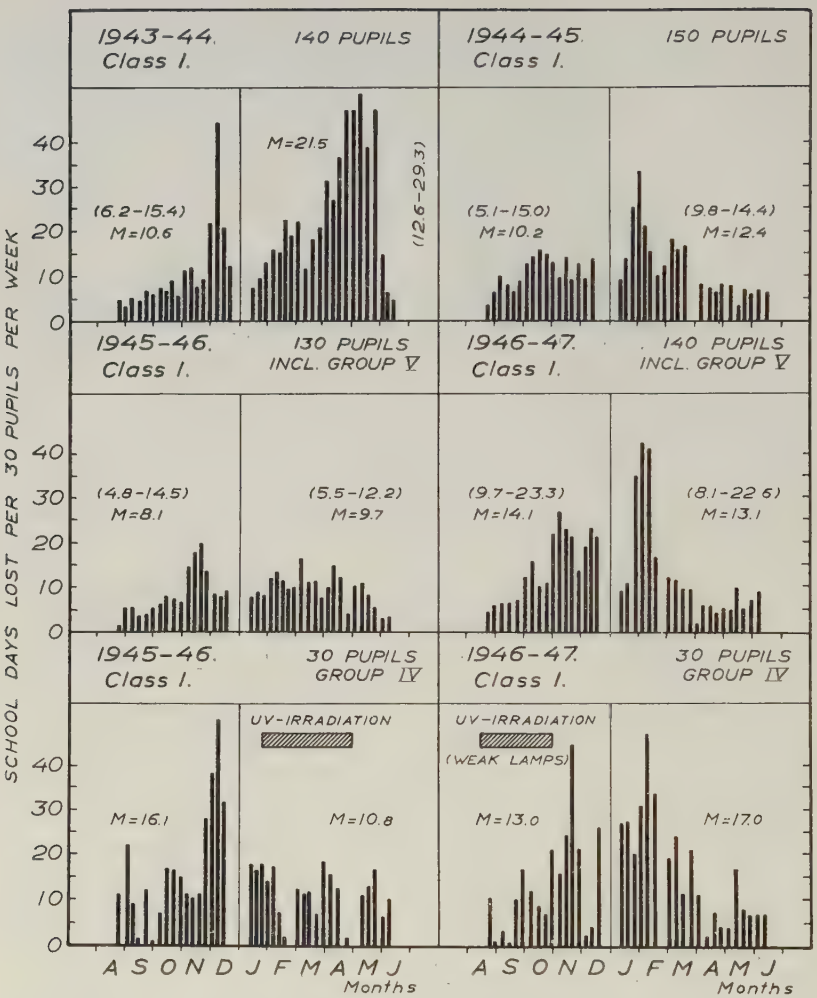

Fig. 53. Lost time due to illness in 1st classes for each week of the school years 1943—1947. Classes with UV-illumination in the two lowest squares (1945—1947).

and the variation range of the different classes (in brackets). The two lowest squares in every figure show the absenteeism recorded for the experimental classes of the investigation; the periods of UV-illumination are specially denoted.

There is a rather *constant feature observed for the annual course of the absenteeism* among the children, which appears in most of the

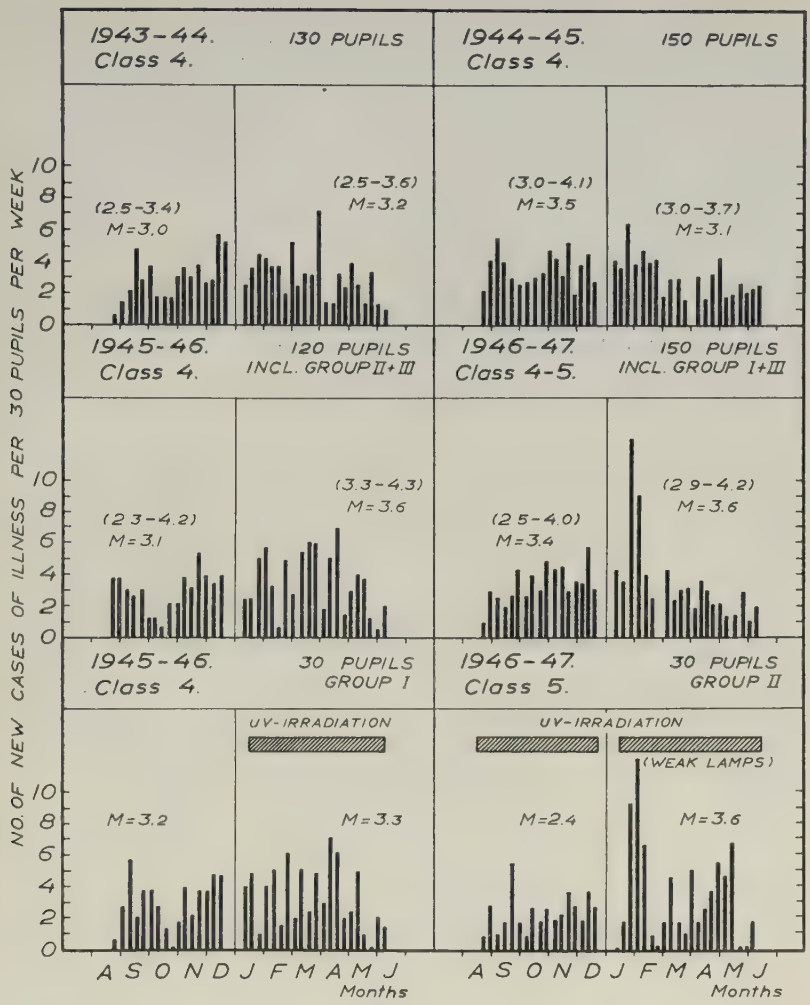

Fig. 54. Incidence of illness in 4th classes for each week of the school-years 1943—1947. Classes with UV-illumination in the two lowest squares (1945—1947).

diagrams and is particularly marked in the older classes. The first 4 to 6 weeks of the autumn term are characterized by a peak in illness, while the last weeks of October almost consistently show a pronounced minimum. From there the absenteeism increases again toward the Christmas holidays. Again, the first weeks of the spring term usually show a marked peak, which may rise to high values

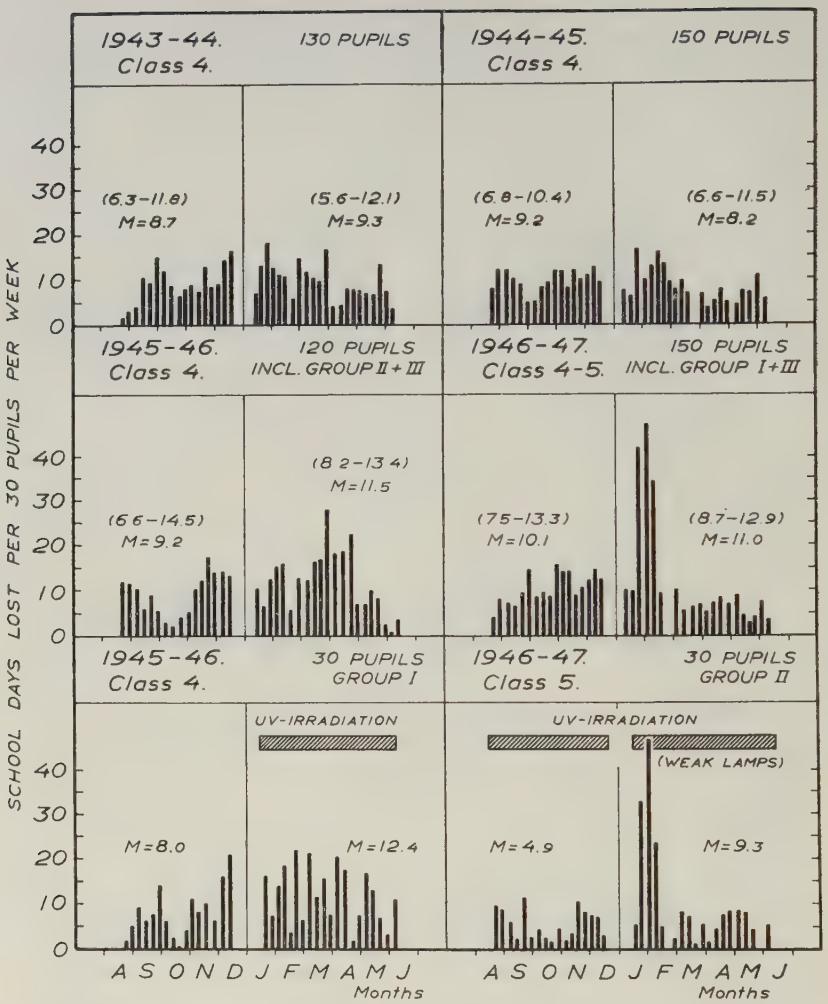

Fig. 55. Lost time due to illness in 4th classes for each week of the school-years 1943—1947. Classes with UV-illumination in the two lowest squares (1945—1947).

(see spring term 1947). A new maximum is often appearing about March, while the latest weeks of the spring term show lower absenteeism. It seems probable that the peaks appearing at the beginning of each term are due to the cross-infections occurring between the children when they are crowded together in the school. The average absenteeism is in most cases higher for the spring term than for the

autumn term. A similar general feature of the course of absenteeism from school is previously found by HJÄRNE (1942) on a comparable but smaller material from secondary schools in Uppsala.

The variations which may occur between different years are clearly demonstrated in, e. g., fig. 53. The time lost in spring 1944 is almost twice that in spring 1945 in these Primary school classes. This difference was less marked for the incidence of illness. Furthermore, the great variations which may occur between different classes of the same grade in the same term are illustrated by the small figures given in brackets for each term record. These give the range of variation of the averages for the different classes included in the total average, denoted by *M*. It is apparent that the deviation found for a single class from the corresponding average must be considerable before any significance can be attributed to it. A difference between different years is still more uncertain, at least for single classes. This must be considered in the interpretations of the results of UV-illumination.

During the spring term 1946, i. e., the first term of the experiment, there was no significant effect on the absenteeism among the older children in the Secondary school class (Group I) provided with UV-illumination (see figs 54 and 55). In the Primary school class (Group IV), on the other hand, the incidence of illness (fig. 52) was markedly low. *It was, in fact, lower than ever recorded for a 1st class in a spring term during the years 1943—1947.* Furthermore, the mean incidence during the spring term was only about half of the mean incidence of the autumn term. Such a relationship has not been seen in any other case. It seems, therefore, justified to assume that the UV-illumination really produced a decrease of the incidence of illness in this class for this period. As mentioned in a previous chapter, the intensity of the ultraviolet irradiation was particularly high in this classroom, which was made apparent by, among other things, the skin pigmentation developing in the children during this period.

The average number of school days lost during the same term (fig. 53) seems not to deviate from the average of the control classes. However, *a marked decrease occurred compared with the preceeding autumn term*, and this latter value was considerably higher in the experimental class during this autumn than the average of the control classes. This indicates that the duration of absenteeism for every incidence was longer in the experimental class, and that the effect of the

irradiation was to decrease the level to about the same as found in the control classes. The reason for the longer duration of absenteeism for each incident illness case in the experimental class may not necessary indicate more severe illnesses; it may also be due to the parents keeping the child at home for a longer time for the same severity of illness, which, in turn, may be due to some differences in their social recruitment. This school is, as previously mentioned, situated in a residential part of the town with its, in general, higher social standard.

During the following autumn term 1946 the ultraviolet lamps in this class had decreased considerably in ultraviolet output, and it was impossible to have them exchanged. No significant effect of this weaker irradiation can be read from the diagrams.

Also the lamps of the Secondary school Group I had now become weak, but new lamps were installed in the classroom of Group II. *There is some evidence that the mean incidence and particularly the mean time lost was decreased by the irradiation in this class.* Group I, with weak lamps, is for this term included in the control groups; there was no indication of an effect of the irradiation.

During the spring term 1947 only the room of the Secondary Group II was equipped with effective UV-illumination, and the lamps had been burning during the previous autumn term. No significant effect may be concluded for this term. The inability of the irradiation to prevent the rapid spread of a respiratory epidemic appearing in January and February is clearly seen from the diagrams.

The results seem to indicate that the UV-illumination employed in the classrooms may to some extent decrease the absenteeism due to illness among the children *when the irradiation intensity is kept at a high level*, namely, that considered as the highest applicable for these cases in the design of the system. Such an intensity may be maintained without damage to the children; the depletion occurring is due to the unavoidable ageing of the UV-sources.

Discussion.

As is emphasized at the beginning of this chapter general conclusions regarding the effect of UV-illumination on sickness-rate in school children must be drawn with great care from this small ma-

terial. The results obtained do, however, provide a stimulus for investigations on a larger scale concerning this possible and favourable effect of the illumination.

The mechanism of such an action may *a priori* be explained in two quite different ways: the irradiation of the children may produce an *increased resistance to infections*, or, on the other hand, the irradiation of the air *depletes the air-borne spread of infections* in the classrooms and thus indirectly decreases the rate of illness. All the evidence is in favour of this latter theory. A marked decrease of the bacterial content of the air has been proved, and the bactericidal effect produced in the rooms is calculated to correspond to about that sanitary ventilation which is found to be effective for control of air-borne infections; this may be particularly valid for the high-intensity irradiations which seem to have influenced the absenteeism in this investigation. Periods of weak irradiation did not show significant effects in this respect while an influence directly on the children, as indicated by the mineral metabolism and physical fitness, were still apparent. It seems probable that the intensities of ultraviolet radiation in the classrooms necessary for preventing respiratory epidemics are considerably higher than those for exerting physiological effects. However, a possible influence on the resistance to infections in the children cannot be completely excluded from the present findings.

It should be emphasized that the air-disinfection of UV-illumination can influence only that spread of infection which is present in the classrooms. During the breaks, in the corridors, and out of school the children may be exposed to still stronger infection doses than in the classrooms, and the total depletion of respiratory infections can for that reason not be expected to be more than partial. The especially marked effect in the Primary school class during the first term of the investigation may to some extent depend on the absence of other classes in the building where this class resided.

Furthermore, the UV-illumination was kept burning only for some hours of the school days. In the 4th class during the spring term 1946 (irradiated Group I) the daily exposure was consistently maintained at 3 hours daily, while the illumination in the Group II during the autumn term 1946 was usually kept burning for longer times a day. This may be a reason why the absenteeism seems to have been more influenced in this latter group.

IV.

General Discussion.

The results obtained during the present investigation on ultraviolet irradiation of interiors in connection with the artificial illumination may be considered from different points of view. The technical section leads to some conclusions regarding the design and arrangement of an artificial illumination with that dual purpose. The physiological section deals with the effects of the irradiation directly on the occupants, in this case school children, and the hygienic section has been concerned with the bactericidal effects and the potentiality of reducing air-borne infections by means of this. For both of these aspects the results permit some conclusions of interest. However, the main question which arises from the investigation concerns the *general value and applicability* of such an illumination. This final decision involves as a further aspect the economic consequences. The possibility must be taken into account that the favourable effects which seem to be obtained with UV-illumination may also be reached with other more practicable and less expensive means. Thus, the ultraviolet irradiation of the children might be replaced by an adequate vitamin supply, and the bactericidal effect might be obtained with an installation of bactericidal low-pressure mercury lamps of considerably smaller total wattage than required for the UV-illumination in the present arrangement.

Leaving these aspects of economy out of the question for a moment the general conclusions obtainable from the present investigation may be summarized in the following way.

General Conclusions.

1. — The present state of knowledge with regard to spectral and dosimetric relations of ultraviolet radiation effects on man provides an acceptable basis for the establishment of the fundamental re-

quirements of the spectral characteristics of the ultraviolet source to be employed for general use in illumination. The knowledge is also sufficient for an estimate of the dimensional design of each installation which must be made with consideration for the time of exposure to the illumination. *The ultraviolet irradiation component may be treated as a separate entity in the design of the system, apart from the illumination component, according to the special photochemical laws valid for biological irradiation effects.*

2. — The ultraviolet radiation may suitably be *resolved into different action components* on the basis of different action spectra; the principle is the same as the resolution of light into different colours. The responses to be separated are the pigmentation effect, the antirachitic effect, the erythema effect, and the ophthalmia effect, all of which concern the direct action on the occupants, and the bactericidal effect, which concerns the action on air and environment. It seems probable that for practical purposes the erythema effect and the antirachitic effect can be referred to the same action spectrum, as well as the photophthalmia effect and the bactericidal effect.

3. — The interpretation of available data on action spectra and threshold exposures has shown that for the direct irradiation of occupants the *short wavelength limit of the radiation* ought to be situated at about 290 mμ. No favourable effects are gained by radiation of shorter wavelengths which are not obtained with greater effectivity and safety by the longer wavelength range. This limit is found in the solar radiation during optimal conditions. In such a radiation the specific erythema component and the antirachitic component, both limited to the range below 315 mμ, may be treated together, i. e., with the same units, and the erythema effect becomes a reliable measure of the antirachitic effect. The risk of photophthalmia is avoided in exposures up to the normal erythema threshold level.

However, the *bactericidal effect* which provides a highly desired action of the illumination is mainly dependent on the prevalence of radiation of wavelengths shorter than 290 mμ. The addition of these wavelengths to the illumination increases the ophthalmia risk in about the same proportion as it increases the bactericidal effectivity.

4. — The investigation has shown that *a compromise is possible, with a resultant illumination of marked bactericidal action without obviously injurious and unfavourable effects.* The displacement of the

spectral intensities from the extreme short wavelength of the specially designed bactericidal low-pressure mercury lamp towards the medium range 260—315 mμ permits the uniform distribution of the radiation in the room. The bactericidal effect obtainable by this in the room is sufficient for the maintenance of a considerable sanitary ventilation potential for reducing air-borne spread of infections.

5. — The basis for the dosimetric design of the irradiation component of the illumination was made by the average normal threshold erythema response. It is shown that *daily exposures to that level of the face and hands of children secure marked effects on mineral metabolism and physical fitness without causing any obvious discomfort.* It seems probable that the same benefits may also be reached with smaller daily exposures, but the higher exposures provide at the same time a stronger bactericidal effect.

6. — One way for the technical arrangement of such an artificial illumination with the dual purpose of providing a simultaneous illumination and irradiation of the interiors is shown. The *medium-pressure mercury vapour lamp* with the outer bulb of special ultraviolet-transmitting glass can be combined with incandescent lamps in such a proportion that a good illumination with pleasant colour of the light is obtained at the same time as both the visible and ultraviolet radiant intensities are suitable for their respective purposes. The total illumination level necessary to provide a pleasant illumination for an erythema-effective exposure is very reasonable. *To produce in about three hours an erythema threshold response in untanned human skin the illumination level required for a pleasant colour of the light is about 300 lux.* This level may be decreased if longer exposures are available. By having the ultraviolet source separated from the main sources of illumination a great range of variation between illumination and irradiation is possible to establish. The source may easily be made so that it radiates a suitable proportion of short-wave, bactericidal radiation.

7. — The technical features of the installation of UV-illumination include the trinity of *source, reflector, and paint.* The reflector should prevent glare and procure a uniform distribution of the radiation, both visible and ultraviolet, for which special assumptions are necessary. Ultraviolet-reflecting paints on ceilings and walls constitute an important factor for the final result with regard to uniformity of irradiation and utilization of the ultraviolet radiation from source

and reflector. These principles are independent of the type of lamp used as source for the ultraviolet radiation.

8. — The *physiological effects* on school children of daily exposures to such an illumination during the winter are found to be very marked in two respects: *mineral metabolism* and *physical performance* (*fitness*). The effects are in the main acting toward a *counterbalance of seasonal variations of these functions*, recorded for the untreated children. These seasonal variations follow an annual course theoretically expected for functions which are subject to a dominant influence of substances photochemically formed and stored in the body by the solar radiation. The optimal phase, characterized by blood-chemically evaluated ideal conditions for skeletal growth, and work-test evaluated high scores of physical fitness, are found in the autumn, around the equinox, when the accumulation of solar-formed substances should be a maximum. The negative phase, with the reverse characteristics, appears for both functions in the spring, around this equinox, when the store of solar substances should have its minimum. This seasonal course is completely cancelled by the ultraviolet irradiation during the winter. *A definite proof is obtained hereby of the important role normally played by the direct action of solar radiation on children during the summer half-year for both of these functions.* The consequences of the poverty of ultraviolet energy in the outdoor daylight during the winter are also apparent from this, which emphasizes the desirability of some form of substitute especially for the countries situated in the north.

It should be pointed out that a high degree of *pigmentation* cannot be expected to develop from exposures to this illumination. The pigmentation effect is mainly limited to the spectral range 315—400 mμ, where the mercury arc lamp radiates only weak intensities, and the dosages necessary for an effect in this respect are too high for convenient application by an illumination system even if other sources are used.

9. — The *mechanism of action* of the radiation must be found for both functions in the action of some photochemically formed substances. It has not been the purpose of the present investigation to find them, but there are several reasons collected which support the view of *a vitamin D mechanism as the primary action*. The possibility of an influence of vitamin D or related substances on muscle metabolism and working capacity provides a great stimulus to further

research. In any case, it is shown that normal unsupplemented winter diet of children is not a sufficient source for these substances and that in this meaning *children suffer from some degree of "solar vitamin" deficiency during the winter and especially the early spring.*

10. — The hygienic effects of the UV-illumination are concerned with its *bactericidal properties* and the possibility of reducing air-borne spread of infections. The contradictory requirements on spectral quality for disinfection efficiency and physiological efficiency placed the bactericidal potentiality of the UV-illumination as a secondary factor in the initial design of it. The investigation showed, however, the inherent possibility in that respect, and it is obvious that *this effect must be treated as a factor of primary importance.* The UV-illumination offers the first artificial illumination system with marked bactericidal effect, and it seems probable that it will find some fields of application for this purpose as a complement and sometimes a substitute for the specially designed bactericidal lamps. *Low-ceiling rooms and rooms with poor air-circulation* are previously mentioned as suitable applications.

Further experiments on this line are going on i day-nurseries, and a new reflector which permits an intense horizontal distribution of the radiation is constructed in order to utilize the bactericidal power to a higher extent than was made in the arrangement used for the school experiments reported here. In this way a high-intense radiation barrier is laid just above eye-level in the room, which produces an effective sterilization of the circulating air at the same time as the illumination below eye-level maintains a considerable bactericidal efficiency.

Practical Conclusions.

Returning to the practical question from the public health point of view regarding the justification of a recommendation of UV-illumination for general use, it is seen that the price of the illumination is outweighed by several distinct advantages. A good artificial lighting is obtained at the same time as favourable physiological effects are produced by the direct action of the radiation on the occupants, and a potential reduction of infection-spread results from the action of the radiation on the micro-organisms of the air. The only disadvantages concern the *high wattage* required for it (about 40 watts per sq. m. floor area) and to some extent the comparatively

high price of the ultraviolet source. The cost of the installation of UV-illumination in, for instance, an ordinary classroom is, however, rather smaller than the cost of an installation of the special bactericidal lamps for upper-air irradiation. The additional cost of installing an artificial illumination of the level reached by the UV-illumination is of about the same magnitude. The high wattage of UV-illumination in the present state is mainly due to the incandescent lamps which provide for the pleasant illumination. For use in schools and similar localities the power may be reduced by keeping only the ultraviolet sources burning during the bright hours of the day. It is found that the colour of the mercury light is then almost completely merged into the daylight. The power of this irradiation is about 10 watts per sq. m. floor area, compared with about 2 watts per sq. m. for upper-air irradiation with low-pressure mercury bactericidal lamps. For this higher price of the UV-illumination the direct physiological effects on the occupants are gained.

The wattage for the illumination component may be greatly reduced by using fluorescent lamps instead of incandescent lamps. With such lamps of comparatively low colour temperature ("white" or "soft-white" types) it seems possible to get a resultant illumination of suitable colour.

Finally, the principle of UV-illumination must be considered with regard to the use of other ultraviolet sources which may be on the market in the near future. The fluorescent ultraviolet lamp is still in the experimental state but appears to be an efficient and suitable source of ultraviolet combinable with fluorescent illumination. The high-pressure mercury vapour lamp emits radiation of a spectral composition which seems to be well adapted for the same purpose (see fig. 21, p. 89). It is still impossible to predict the bactericidal effect obtainable by these sources.

It seems probable that some of the physiological effects of UV-illumination may be reached by the simple administration of sufficient doses of vitamin D to the children during the winter. From the economic point of view this would obviously have distinct advantage over the UV-illumination. The final decision must, however, be postponed until further investigations are made on this fundamental question.

The natural field for the application of UV-illumination would tentavively be *schools, day nurseries, and similar localities where*

children are brought together especially during winter months. In hospital wards with the patients having their faces and eyes directly exposed to the radiation from above, there may be risk of harmful effects if such high intensities are used as in the present experiments. The utilization of the illumination for homes is still limited by the cost and the wattage. The damaging effect on flowers and plants may be a further disadvantage for the home application. The control of over-exposure cannot be provided in the same degree as in public localities.

The use of UV-illumination in *localities for adults*, as in industry, under-ground factories, etc., is probably justified mainly by the bactericidal properties of it. The growing organism may be expected to be more sensitive to the deficiency of biologically-active radiation during the winter than the adult organism, and the desirability of a supplementary ultraviolet irradiation of adults cannot be stated with the same certainty as in the case of children. It should be pointed out that the average industrial worker receives almost no ultraviolet radiation for the most part of the year. He is exposed to outdoor daylight only in the morning and afternoon hours when practically no ultraviolet radiation reaches the earth, and no such radiation penetrates to indoor working places. There are obviously no apparent harmful effects developing from this, which, however, would probably be the case for children. Workers in under-ground factories, miners, etc., are not subject to worse conditions than the average industrial worker in this respect of short-wave ultraviolet rays. It may, however, be possible that the deprivation of ultraviolet radiation does manifest itself by some degree of "spring fatigue" also in adults. Tests on working efficiency as applied here on children would provide one means of deciding this.

The bactericidal purpose alone may in most industrial localities be reached in a more economical way by means of the special low-pressure mercury bactericidal lamps.

Summary.

I. Introduction.

Chap. 1. *The Basis and Purpose of the Investigation.*

The purpose of the investigation was to study the physiological and hygienic effects of the addition of biologically-effective ultraviolet radiation to the general illumination of interiors. It is emphasized that from the physiological point of view this problem is of special interest to countries situated in the north where the natural supply of this radiation is poor for long times of the year.

Chap. 2. *A Brief Survey of Ultraviolet Radiology.*

A brief review is given of ultraviolet radiology with special reference to sources of ultraviolet for biological purposes, and the biological effects on man of ultraviolet radiation. Besides the local effects, such as erythema, pigmentation and photophthalmia, irradiation is proved to be a potential factor for mineral metabolism and for muscular working metabolism.

Chap. 3. *Hygienic Applications of Ultraviolet Radiation.*

Previous attempts to provide for ultraviolet radiation in interior localities by means of ultraviolet-transmitting window glass and artificial sources are reviewed; the former is mostly inefficient, the latter is not yet adequately studied. Results obtained in large-scale investigations on the benefits of artificial sunlight treatments in the usual way with 'solaria' have given no evidence of decreased sickness-incidence or duration. Physiologically estimable increases of muscular working capacitity may, however, result. A modern hygienic application of ultraviolet radiation is made by the radiant air disinfection for control of air-borne spread of infections. An efficient source for this is the bactericidal low-pressure mercury arc.

II. The UV-Illumination System.

Chap. 4. *The Basic Design of the UV-Illumination System.*

The design of the UV-illumination system was made with careful consideration of spectral and dosage relations of ultraviolet irradiation effects on man, of which a detailed account is given. The importance of the time-factor is stressed. A system of terms and units intended for practical purposes is described. It was shown that for the action on the occupants the short-wave spectral limit of the radiation ought to be situated at the wavelengths 280—290 mμ, although the prevalence of shorter wavelengths is accompanied by the benefits of a stronger bactericidal effect on air and environments. The system was designed for classrooms and so that the daily exposure should approximately reach the erythema threshold dosage on the face and hands of the children.

Chap. 5. *The Technical Arrangement of the UV-Illumination System.*

The technical arrangement comprised of radiating source, diffusing reflector, and reflecting paints on ceilings and walls. The source consisted of a medium-pressure quartz mercury-arc enclosed in an outer bulb of special glass permitting the emission of radiation in the medium-wave range 280—315 mμ but mostly absorbing radiation of shorter wavelengths. A pleasant colour of the illumination was obtained by supplementary incandescent lamps. A type of reflector, and some ultraviolet-reflecting paints, developed during the investigation, are described. The total wattage required for the illumination of an ordinary classroom of 50 sq. m. floor area amounted to about 2 kilowatts, most of which was due to the incandescent lamps.

Chap. 6. *The Radiation Climate of the Experimental Rooms.*

The intensities of ultraviolet radiation obtained in the classrooms equipped with UV-illumination were computed and experimentally controlled to be at the level required for erythema-effective exposure in 3—5 hours. In the more intensively irradiated room the children developed a slight but visible degree of pigmentation. No single case of harmful effects occurred in spite of the comparatively high intensity of short-wave ultraviolet radiation.

Chap. 7. *The Physical Methods Employed.*

The physical methods employed for measurements of spectral energy distribution, spectral transmittance and reflectance and spectral radiant intensities are described. A new semi-quantitative spectrographic method for the direct estimation of spectral energy distribution is developed.

Chap. 8. *A Comparison with Daylight Ultraviolet Conditions.*

Data available on the spectral energy distribution in sun and sky radiation at different elevations of the sun were used to give a basis for comparison with the artificially created indoor ultraviolet radiation climate. The daily amounts of antirachitic radiation were computed for different seasons and different latitudes. Practically no such radiation reaches the earth during 4—5 of the winter months at the latitudes of Scandinavia. The maximal annual amounts, calculated for a presumed cloudless year, increase markedly towards southern latitudes. The artificially made radiation climate offers some resemblance to the natural outdoor radiation conditions at a sun elevation of 30 degrees with respect to antirachitic and erythemal effect but is much weaker in pigmentation effect.

III. The UV-Illumination Effects.

Chap. 9. *A General Scheme of the Investigation.*

The investigation of physiological and hygienic effects of the UV-illumination was carried out in a Primary and a Secondary school of Uppsala during a period of $1^1/_2$ years. A total of 220 children aged about 7 and 10 years, respectively, were involved in the investigation, 120 of whom received ultraviolet irradiation for some period of time. The methods of the statistical treatments and the reproduction of the results are described.

Chap. 10. *Effects on Some Constituents of Blood.*

Blood analyses on the children were carried out with regard to the levels of haemoglobin, total calcium, inorganic phosphorus and alkaline phosphatase. Six series of determinations were made, distributed over different seasons of the year. A seasonal variation in

untreated groups was recorded for the plasma level of calcium, with a maximum cencentration in September or October and a minimum concentration in March, and for the plasma phosphatase activity, with the seasonal course reversed to that of calcium. In the irradiated groups these seasonal variations were completely counterbalanced, and the concentrations maintained at the normal autumn levels during the winter. The levels of inorganic phosphorus as well as of haemoglobin showed no significant variations with the seasons, and no pronounced effects were obtained by the ultraviolet irradiation.

The administration of a single dose of 250,000 I. U. of vitamin D (calciferol) to a small group of non-irradiated children in midwinter did not significantly influence either of these blood levels.

The interpretation reveals the dominant and selective importance of ultraviolet radiation for the maintenance of the mineral metabolism at the optimal level found in autumn in these school children. The seasonal variations are explained as due to the state of accumulation of solar-formed substances in the body; the normal winter-diet is not sufficient to replace the lack of natural ultraviolet radiation. The mechanism of action of the radiation, whether solely due to formation of vitamin D or if a specific hypercalcaemic effect is also involved, is discussed.

Chap. 11. *Effect on Physical Fitness.*

The scores of physical fitness were obtained for Secondary school boys in irradiated and control classes (60—90 boys) in six series of determinations applied at different seasons. The test comprised a set of cardiovascular criteria applied in the submaximal phase of a continuously graded work on a bicycle ergometer. Detailed accounts of the method and the experimental controls of reliability carried out are given. Untreated control children showed a tendency to a seasonal variation in physical fitness, with the highest scores in autumn and lowest scores in spring. By means of the UV-illumination the scores were maintained or rather increased during the winter, and the difference between irradiated and control children was especially marked in the spring.

The vitamin D dosage administered to the control group strongly indicated an effect in the same direction as obtained by the irradiation.

The results emphasize the importance of solar ultraviolet radiation and its accumulation in the body, probably in the form of vitamin D, as a factor for the general well-being of children. Decrease of working capacity seems to constitute a sensitive sign of vitamin D deficiency. The findings are discussed in the possible relation to "spring-fatigue."

Chap. 12. *Effect on Air-Borne Bacteria.*

The bactericidal effect of the UV-illumination was studied on a laboratory scale by infection-chamber experiments, and by counts of total bacterial concentration of the air in the experimental and control classrooms. A physical interpretation of radiant air disinfection is made with special reference to the uniform irradiation of the room obtained with UV-illumination. Theoretical as well as experimental evidence is given for a killing-rate of respiratory air-borne organisms in the zone of the occupants corresponding to an equivalent ventilation of about 30 air-changes per hour. The average count of total bacteria in irradiated classrooms was found to be about half the count in control classrooms; the reduction of most pathogenic bacteria may be expected to have been still greater.

Chap. 13. *Effect on Absenteeism.*

Records of absenteeism due to illness were made for each week of the terms for different groups of school children in Uppsala for the years 1943—1947. The features of the seasonal course are discussed. On the basis of these statistics it is shown that the UV-illumination in some cases caused a marked reduction of absenteeism; the effect in this respect seemed to depend on the intensity of the irradiation and ceased when the ultraviolet sources began to age. The effect is ascribed to the air-disinfection obtained by the use of the UV-illumination.

IV. General Discussion.

The results are discussed with respect to the general conclusions regarding technical, physiological, and hygienic aspects of the UV-illumination which are emerging from the investigations. An application of this kind of illumination seems recommendable especially in localities as schools and day-nurseries where children are brought together. The bactericidal effect, particularly, may justify its use in other cases also.

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Errata.

***Page 22**, 7th line from below,*

for E. P. WIDMARK, *read* E. J. WIDMARK

***Page 29**, 9th line from above,*

for 1822, *read* 1882

***Page 51**, 8th line from below,*

for 340—880 mμ, *read* 340—380 mμ

***Page 86.** Formula (6) should be*

$$z = k\,(1 - e^{-\frac{a}{k-a}\tau}) \tag{6}$$

***Page 108.** The uppermost formula should be*

$$\sigma^2 = \frac{(n_1 - 1)\,\sigma_1{}^2 + (n_2 - 1)\,\sigma_2{}^2}{n_1 + n_2 - 2}$$

***Page 157.** Formula (8) and (9) should be completed according to*

$$\frac{P}{P_0} = e^{-\frac{\frac{F \cdot R}{V} \cdot t}{U}} \tag{8}$$

$$\frac{P}{P_0} = e^{-\frac{\frac{F \cdot R}{U} \cdot t}{V}} \tag{9}$$

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